The Fore*sight* Programme

Electronic Materials and Devices

Report of the Defence and Aerospace National Advisory Committee

March 2002

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Chairman’s Foreword

This National Advisory Committee on Electronic Materials and Devices was established in 1999 in order to develop and communicate an understanding of the needs and priorities for research and technology development, to maintain a view of UK competitiveness, and to advise the Defence and Aerospace foresight panel on electronic materials and devices. The scope is of necessity broader than that of most Advisory Committees, in that development in electronics cannot now be driven by the relatively small defence and aerospace markets, which between them probably account for only 1% of the total market. The Committee has therefore taken a broader view of the electronics industry to include all the major commercial influences. This approach follows that established by the previous panel, who published a report on Electronic Materials for Defence and Aerospace under the Chairmanship of Professor Whatmore in 1998.

One of the problems with the topic is the broad range of materials that have to be considered. As Chairman, I have been greatly indebted to all the Committee members for their expertise in providing inputs across all the materials and technologies relevant to the sector. Inevitably, the choice will to some extent reflect the personal expertise and interests of the Committee members, but their depth of technical knowledge can be seen in their contributions to this report. The robustness of the conclusions of the report in the face of the market fluctuations over the last eighteen months is a tribute to their broad perspective.

One problem that a Chairman has with this topic is that of preventing meetings from turning into a litany of what is wrong with manufacturing industry in the UK. This has been avoided in the report, except for some brief comments in the executive summary, but certainly there are two general themes that have caused concern. The first is the sale of large parts of large technically advanced manufacturing centres within the UK, leading to a loss of direction for R&D, and the other is the concern over the number of people choosing science and engineering as a career. The two may well be related, but it is clear that no recommendations from this Committee can add to the debate.

I would like to thank all the members of the Committee, and the Institutions for which they work for their time and effort in attending meetings and contributing to this report. The main concern now, within the new framework for Defence and Aerospace Panels, is to ensure that recommendation in the report lead to concrete actions. This will be the main issue for future meetings of the Committee.

Andrew Phillips

March 2002

Executive Summary

This report by the National Advisory Committee on Electronic Materials and Devices focuses on seven topic areas: Silicon, Compound Semiconductors, Interconnection and Packaging, Electro-Optics and Displays, Sensors and Microsystems, Nanotechnology, and Non-Semiconductor Electronic Materials. Much of the basic information on these technologies was presented in the earlier reports completed in 1998: Materials Foresight on the Electronics Industry, and the Defence and Aerospace report on Electronic Materials. Although some updating of the earlier material is necessary, in general the earlier identification of priority areas remains valid.

There have been significant changes in the Silicon and Compound Semiconductor markets.The last remaining UK owned Si fabrication facility, GPS, has been sold to Mitel (now Zarlink) and a downturn in the Si IC market has resulted in the closure of a number of UK operations. However, many design houses have been established in the UK, accessing leading-edge technologies on a Foundry basis. This design-based approach is also now being followed by Zarlink.

The market for III-V materials expanded rapidly in 2000, driven by the communications market, for both opto-electronic and microwave components, but suffered a subsequent downturn in 2001. This has resulted in significant problems world-wide in matching requirements to resources, for materials as well as trained personnel. Within the UK, Filtronics and IQE expanded production capability. The communications market also drove the demand for Micromachined Passive Optical Components, providing a specific focus for MEMS technology, but reflecting the cyclical character of that market. An encouraging aspect of the communications market is the increasing tendency for the exploitation of innovation by start-up companies.

Non-semiconductor functional materials such as piezo- and ferroelectrics were not given sufficient emphasis in the earlier reports: They form the basis of a world market of over $20B, with a strong presence in the UK, although recent developments in new piezoelectric materials in the US and Japan need to be matched if this is to be maintained.

There is increased globalisation in the packaging market with major developments driven by the communications and other civil markets, paralleling the situation in silicon and compound semiconductor active devices. Within this environment, access to key technologies is proving problematic. UK defence and aerospace industries are finding it increasingly difficult to source suitable components for their applications, and are unable to influence the component manufacturers because their requirements account for only a tiny proportion of the total volume.

It is clear that strong innovation within the UK is not being exploited by larger companies. The reasons for this have been well rehearsed: emphasis on profit rather than growth with lack of longer term strategy and investment in R & D, lack of governmental support during the early high-risk phases of development, and a culture that favours financial engineering at the expense of real engineering and manufacturing.

Another conclusion of the committee is that there is an urgent need to build up the skills base in the UK, concentrating on those aspects which can give a real return on investment and also support the needs of industry (with particular emphasis on the defence and aerospace sectors).

The committee makes a number of recommendations in the vital areas of semiconductor development and access.

- It is essential to establish within the UK a state-of-the-art semiconductor processing facility, providing advanced technology for the processing under production conditions of both silicon and III-V materials. The Centre will provide a facility for industrial development, prototyping and low-volume production, and also act as a major academic research resource. In addition to semiconductor materials, the Centre will provide for the processing of other materials such as those used for sensors and microsystems. The equipment must be such as to allow the Centre to participate fully in European programmes, particularly in view of the increased emphasis on large projects and networks in the next call. The cost of such a facility is approximately £100M, much less than for a high-volume silicon facility, and there is the clear expectation that this cost will be recovered through subsequent industrial exploitation within the UK.

- The facilities required should be recognised in the DTI OST Large-Scale Facilities Roadmap and funded accordingly as a key technology for the future.

- UK Universities should be further encouraged to collaborate and co-ordinate their research programmes in electronic materials and devices, particularly when advanced and expensive facilities are necessary. The role of Central Facilities such as RAL, Sheffield and Southampton should be examined with a view to improving collaboration, as part of a strategic EPSRC programme.

- The need for trained personnel is a continuing theme in all areas of electronic materials. The recent increase in PhD salaries should help, but there is a need to increase the salaries and improve the career structure of research associates within UK Universities.

Electronic Materials

1. Introduction

- This report by the National Advisory Committee on Electronic Materials focuses on seven topic areas: Silicon, Compound Semiconductors, Interconnection and Packaging Electro-optics and Displays, Sensors and Microsystems, Nanotechnology, and Non-semiconductor Functional Materials. There is inevitably some overlap, particularly between Electro-Optics and Semiconductors, and it is also important to distinguish between the markets for materials, and the market for fabricated devices. In silicon, for example, the wafer market is only about 3% of the semiconductor component market.

- Much of the basic information on technologies was presented in the earlier reports completed in 1998: Materials Foresight on the Electronics Industry, and the Defence and Aerospace report on Electronic Materials. A certain amount of updating of the earlier material is necessary, but in general the earlier identification of priority areas remains valid.

- This report is intended to be more concise and focussed than the earlier two reports, with a shorter list of well-defined recommendations, in the hope that it will have more impact.

2. Silicon

Market and Technology Trends

- Although there was a strong recovery world-wide in the Si IC market in the late 1990s, the cyclical nature of the industry is illustrated by the succeeding downturn in 2000-1. The silicon market peaked at about $150B but is now barely keeping above $100B. This downturn has resulted in the closure of a number of UK operations, as did previous downturns, leaving the UK in a vulnerable position. The strongest companies now are those that maintained investment during leaner times.

- The last remaining UK owned fabrication facility, GPS, has been sold to Mitel (now

Zarlink). The 0.35mm technology is two generations behind the technologies available in the US and Far East, and at least one behind the major European companies (STM, Infineon, Philips). Most have benefited from direct or indirect Government support.

- Many small design houses have started up in the UK, attempting to access leading-edge technologies on a Foundry basis. This design-based approach is also being followed by Zarlink. However, most of the large US and European companies do not offer a general foundry service, particularly at 0.18mm, so that design capability is reliant on limited Far East capacity. Traditionally, funding from military and aerospace sources has been used to support process development within the UK, but this has essentially stopped following several strategic reviews.

- Performance of Silicon is expected to continue to increase over the next decade, after which real physical limitations are foreseen. The Si road map provides a coherent plan for the development of processing equipment, but the lack of leading-edge UK manufacturing capability handicaps UK suppliers.

- SiGe is now available on a foundry basis in Europe and North America, although not in the UK, to give a performance enhancement of about 20% over Silicon bipolar devices. The market is expected to increase to about 9% of the Si market by 2005.

UK Strengths

- There is still a manufacturing Si capability within the UK, even though overseas-owned companies have closed at least six UK operations in the last three years.

- University research is maintaining some degree of competitiveness in Si and Si/Ge, although research is hampered by ageing or limited facilities.

- There are available skills in Universities and Industry in process and device modelling. Glasgow for example is recognised as a world authority on modelling the operation of very small transistors.

- The UK has significant strength in design, with a number of design houses (such as ARM and SSSL) that use a range of Si processes. These are high-added value operations exploiting Intellectual Property in designing solutions.

- A new company (IQE Silicon Compounds), is developing significant business in supplying both Silicon and Si/Ge epitaxial wafers.

UK Weaknesses

- The UK share of the world production of Si chips is decreasing as a result of decisions made by non-UK based companies.

- University research into silicon technology is becoming increasingly difficult without access to state-of-the-art processing equipment, and without the drive from indigenous industry.

- Similar concerns are important for support industries involved in equipment manufacture, device and processing modelling, and design software.

Opportunities

- The rapidly increasing costs incurred in the development of new processes are leading to increased collaborative pre-competitive research. For example, much of the European Si industry is using IMEC (Belgium) as a centre for development. This example is important in illustrating that cutting edge research is possible even in the absence of national industrial capability: A co-ordinated UK research programme with strong links into IMEC could be developed to provide access to state-of-the-art technology.

Threats

- Technological obsolescence within the research community, combined with the cost of new equipment, means that it is increasingly difficult to provide suitable training within the University system.

- Increased reliance on Far Eastern technological capability is a major risk, particularly as these economies move to increased added value in their products. Increasing intelligence in silicon devices, and continued adoption of silicon-based systems means that the UK will become uncompetitive in many other manufacturing areas, including automotive, aerospace, military, domestic and consumer markets.

- For defence and aerospace applications there is a more general problem of obtaining access to advance technologies because of the very small volume requirements in comparison to the computer and communications markets.

- The lack of indigenous industrial development makes it hard to give an obvious justification for University funding for cutting edge technology.

Comments and Recommendations

- It must be recognized that the case of Si is very different from that of other electronic materials, not just because it dominates the global market, for electronic materials but also because from the UK perspective there is almost no industrial R & D. The most important requirement for encouraging inward investment is, therefore, to provide an appropriate skill base in advanced Si technology within the UK.

- Training in state-of-the-art technology requires an upgrading of the UK research capability to provide some state-of-the-art research capability. The cost of equipment inevitably means further co-ordination between Universities and other institutions (such as RAL). The SiGe initiative provides a partial model, although the number of participating organisations should be reduced, and some way found of including significant industrial input (such as the IMEC model).

- This committee recommends that a Semiconductor Research Centre should be established in order to maximise the return on research investment, and to allow full participation in European programmes. Further, a research centre with a fully capable process could provide competitive devices for research, small volume applications and new market development.

3. Compound Semiconductors

Market and Technology Trends

- The market for III-V materials expanded rapidly in 2000 on the back of previous investment, driven by the communications market, even though there was a major downturn in 2001. The growth resulted in significant supply problems world-wide in 2000, particularly for substrates and epitaxial material.

- Within the market for microwave devices, MESFET devices are being replaced by HEMTs and HBTs for improved performance. The market for opto devices such as lasers and detectors, is also seeing rapid growth.

- Within the UK, Filtronics has established a plant in the previous Fujitsu Si factory to produce components for mobile phones, with a projected capacity of over 100,000 6" GaAs wafers per year. Marconi Caswell also upgraded to 6" wafers for opto-electronic and microwave components, and the apparent intention is that this will continue under Bookham ownership.

- On the wafer supply side, IQE (formed by a merger between EPI, Cardiff, and QED, USA), is rapidly expanding production capability for MOCVD and MBE material.

- Worldwide, the major development in GaAs technology is the change to 6" wafer processing to supply the simultaneous demands for higher volume and lower cost. This development also allows GaAs facilities to use previous generation Si production equipment.

- The trend to shorter gate lengths has been supplemented or even replaced by the development of metamorphic materials. These allow high performance devices to be fabricated using GaAs, without the need to use InP substrates or gate lengths below 0.15mm, but exploiting the higher mobility and saturation velocity in InGaAs materials. There is little sign that materials with even narrower bandgaps will be developed for electronic applications in the foreseeable future.

- The development of GaN-based materials for blue light-emitting diodes and lasers has generated a large market, with four companies (one Japanese, two US and one European) each producing up to 50 million LEDs per month. There is active development within the UK at QinetiQ on GaN for microwave devices.

- UK industry has been involved in supplying equipment for GaN material growth and processing. Thomas-Swan, supplying MOCVD equipment, has recently been acquired by Aixtron, the major European manufacturer. This supplements the considerable existing industrial activity in processing equipment and materials supply for other III-Vs.

- The announcement in 2001 of a strategic link between IQE and Motorola to exploit GaAs on Silicon has major implication for the GaAs market, and is precisely the kind of topic that a central Semiconductor Research Centre could address.

UK Strengths

- There is a significant and expanding manufacturing base in components for the communications market, both microwave and optoelectronic.
- A strong University research base for materials growth and characterisation, device modelling, measurement and circuit design has been established. This is slowly being extended to the widebandgap materials such as GaN.
- A number of SMEs developing software for design and device characterisation.
- A strong background in materials growth and characterisation.

UK Weaknesses

- 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.
- Support for state-of-the-art growth and processing equipment within Universities lacks strategic direction.
- There is almost no industrial involvement in the high-volume manufacture of optical components such as LEDs, and so little chance to exploit GaN technology.

Opportunities

- The continued development of high-data rate communications provides major opportunities for companies such as Bookham, Filtronics, Nortel and Agilent to build on the UK research base in III-V and other materials to establish a strong manufacturing base.
- GaN has the potential to be a disruptive technology in many civil, defence and aerospace system applications. The technology is being actively pursued in the US, and can be seen as a major opportunity for, as well as a threat to, European defence companies.
- For GaN, a new Joint Venture is being formed between QinetiQ and IQE, which will lead to the exploitation at IQE of the epitaxial material technology being developed

by QinetiQ

Threats

- A shortage of skilled personnel is already apparent, particularly for material growth, process development and RF design.

- As in the case of Silicon, there are difficulties in ensuring access to key technologies for the limited volumes needed in defence and aerospace. It is clear that to maintain a technology solely for such applications is prohibitively expensive, but at the other extreme, a technology with high-volume commercial applications is unlikely to be offered as a low-volume foundry process.

- The long-term supply of key components for military applications cannot be guaranteed, in view of the large difference in time scales between military procurement and the turnover in commercial technology.

Comments and Recommendations

- Processing requirements for III-V materials are becoming increasingly demanding, involving sophisticated and expensive equipment. Capability within the UK is fragmented, with no centre able to provide a complete range of facilities and expertise. This fragmentation is an inefficient use of resources, and a major recommendation of this Committee is that a state-of-the-art semiconductor processing Centre should be established to provide advanced technology for the processing under production conditions of both silicon and III-V materials. The Centre will provide a facility for industrial development, prototyping and low-volume production, and also act as a major academic research resource. In addition to semiconductor materials, the Centre will provide for the processing of other materials such as those used for sensors and microsystems, and it is important to establish strong links with any other centres in these areas. The equipment must be such as to allow the Centre to participate fully in European programmes, particularly in view of the increased emphasis on large projects and networks in the next call. The centre would provide;

  i. a focus for the development of new technologies collaborating with Universities and Industry

  ii. a test-bed for the demonstration of new semiconductor processing equipment in collaboration with manufacturers.

  iii. an incubator for new start-up companies by providing standard, controlled processing for electronic and opto-electronic technologies.

  iv. a centre of excellence for silicon processing that could collaborate on equal terms with other European centres.

The cost of such a centre is approximately £100M, much less than for a high-volume silicon fabrication line, and there is the clear expectation that this cost will be recovered by subsequent exploitation within the UK.

- Both within the UK and world-wide (with the possible exception of the US) it is no longer possible to start from system needs in defence and aerospace applications to identify specific technology requirements at the component level. The rapidly reducing level of support for component development together with the relatively small market, particularly in comparison to the very large communications market, means that Defence and Aerospace requirements have almost no impact in determining the future direction of technology development.

- There are three major concerns over the use of commercial processes for defence and aerospace applications: access, reliability, and long-term procurement. Defence and aerospace development should complement the development of available commercial processes, ensuring that funding is used to ensure access to the technologies. Collaboration between users would increase volume requirements if issues of confidentiality can be solved. Reliability should not be a problem: Commercial reliability requirements are at least the equal, at the process level, of those for military or space applications. What is clear is that there will only be development of specific military and aerospace technologies where these are strategic, as is the case for cooled IR arrays, or radiation-hard circuits. The problems of long-term procurement can only be solved by adopting a more flexible procurement policy that accepts the need for continuing redesign.

- There is a case for coordinating and focussing research work in Universities in a more structured way. The MURI projects in the US provide a relevant example of combining collaboration with competition, whereas there is evidence that within the UK the Research Assessment Exercise (REA) reduces collaboration by introducing competition both at the Departmental level within Universities, and between Universities.

4. Interconnection and Packaging

Market and Technology Trends

- The situation in packaging resembles that in Silicon in that technology is driven primarily by the high volume commercial markets, while at the same time packaging and interconnection technology is of strategic importance for future defence and aerospace electronics development within the UK.

- Increasing data rates in optical and high-frequency microwave communications have imposed much more severe constraints on the interconnection of optical and electrical components, adding to the already severe problems involved in packaging and aligning optical components. There is a major expansion in this area, involving UK-based companies such as Bookham, Nortel, and Lucent.

- There is a rapid adoption of Chip Scale Packaging (CSP), driven by the mobile communications industry because of the smaller package footprint, lower pressure on next level interconnection, and standardisation of the chip to board interface. Some manufacturing expansion in single chip packaging has occurred in Europe in the last two years, with notable activity by Atlantic in the UK, CS2 in Belgium and by

ST in Malta.

- The use of multi-chip module (MCM) technologies has grown significantly on a global basis, with Ball Grid Array laminate packaging employed for digital and mixed signal applications, and ceramic packaging for RF applications with integrated passive components. The first steps to exploit thin film integrated passive MCM technology in Europe have begun.

- Performance, functional density, environmental and legislative pressures are driving the printed circuit board (PCB) industry to adopt High Density Interconnects, build-up board technology, improved stability and lower dielectric constant laminates and to introduce alternative flame retardant materials.

- There is a growing convergence between chip level and board level assembly technologies, with the emergence of laminate based chip package structures and increasing use of bare die.

- The electronics systems for the civil and military markets continue to share common requirements with those of the latest portable wireless telephony, data and internet access products in demanding ever greater functionality, higher performance and lower cost in smaller and lighter formats. These demands have been satisfied by advances in device technology, and by the introduction of smaller, lower overhead packaging formats and smaller discrete passive components, interconnected using advanced hybrid, multichip module and HDI PCB technologies.

- The levels of system and sub-system integration and the growing pressures to reduce time-to-market in civil, military and commercial markets have placed ever-greater emphasis on right-first-time implementations. This has increased the need for robust design routes and the need for soundly based models and simulation routes for the interconnection and packaging structures employed in system design.

Strengths

- The level of activity in single chip packaging and in advanced PCB technology for high volume applications has increased in the UK in the last two years.

- The UK maintains a sound capability in modelling, design route development and design of functions, sub-systems and systems that employ a wide range of active devices together with increasingly diverse interconnection and packaging components and structures.

Weaknesses

- The activity in the UK in the provision of materials and processes for packages and interconnection structures has continued to decline while the major developments in packaging materials and technologies are increasingly made overseas and are directed at higher volume market areas.

- Undue reliance on technologies from non-UK sources for systems requiring special developments in interconnection and packaging and the related issue of poor leverage with such companies when modest volume defence and aerospace applications are involved.

Opportunities

- The opportunities presented in the high data rate communications sector for compound semiconductors also imply opportunities for the associated assembly, interconnection and packaging structures required to support and interconnect these devices

- The convergence of chip level and board level assembly will provide opportunities for the UK to increase its presence in these areas, leveraging recent developments in HDI PCB technology and single chip packaging.

- The increasing level of automation in chip and board level assembly provides a far more level playing field for the UK to expand its activities in interconnection and packaging since labour costs are no longer dominant

Threats

- The major issue that confronts the UK defence and aerospace industry, and UK suppliers into civil and military markets is the increasing globalisation of the electronics industry at the chip, package, circuit board and system level. The UK electronics industry remains a substantial and growing business, but is increasingly under foreign ownership within a multinational company culture.

Recommendations

- Focus research and development resources on those areas that complement available packaging and interconnection capabilities in the UK, structured to meet the needs of the defence and aerospace sector whilst benefiting the higher volume suppliers so as to encourage the continued availability of their technologies. The main aim must be to ensure that a suitable materials supply base, design and manufacturing infrastructure is available to meet defence and aerospace sector needs.

- Stimulate academic research into interconnect and packaging technology through both managed and responsive modes, as in the recent IMI initiative.

- Draw together existing activities in interconnect and packaging technology by building on, and expanding, existing networks. Activities and networks in this area should be co-ordinated and driven by representatives of the appropriate defence and aerospace systems companies and end users to ensure suitable focus.

- A UK focus for Interconnection and Packaging should be created, linked to and supporting initiatives in Semiconductor Technology. The recent Faraday initiative based at TWI is a good base for such a focus.

- Establish a strategic view of critical materials developments in packaging and interconnection and involve the SME supply base in joint industry-academic-government supported programmes

- Develop a systems approach to interconnection and packaging involving multidisciplinary teams, in materials research, electronic engineering, mechanical engineering and production engineering in order to achieve competitive advantage

- Studies of high functional density systems should be undertaken by a combined industrial and academic grouping, with particular emphasis on high density interconnection, thermal management, integrated passive components, the development of "foundry" style design and manufacturing capabilities and highly robust design methodologies. The concept of modularity and re-use are also well supported by such technologies.

- A further area of interconnection and packaging technology that is strongly materials related is that of reliability. The fundamental, often long-term, nature of reliability work is of great interest to both the defence and aerospace sector, and to the high volume commercial market, providing a link between the two.

5. Electro-Optics and Displays

Market and Technology Trends

- Displays provide one of the vital interfaces between man and machine in both professional and consumer goods. Whilst it is a market in its own right with specific customers and needs, the displays market is dependent on the trends in the overarching IT & Electronics systems market which is subject to strong cyclical behaviour.

- The world-wide displays market in 2000 was $54.8B, dominated by Cathode Ray Tubes (CRT), (51% market share), and Liquid Crystal Displays (LCD, 45%), with a small fraction (4%) attributed to other technologies such as Plasma-, Field emission- and Polymer displays.

- Continuous technical developments to the CRT, coupled with a low manufacturing cost, have made it difficult for competitors to displace this mature, incumbent technology during the last 30 years. It is forecast, however that by 2003 the compelling advantages of LCDs in a range of products such as notebooks, mobile phones, desktop monitors and TVs will result in LCD sales outstripping those for the CRT. The major growth in LCDs will be from active matrix devices with forecast sales of £41B by 2005.

- UK has played a major role in the research and development of LCD materials and device technology, especially the pioneering work of Hull University and RSRE Malvern (now QinetiQ) in the 1970s and '80s. However, apart from the successful exploitation of liquid crystal materials by BDH (now Merck), these early developments were not taken up by UK industry: Industries in The Far East were the main beneficiaries of these UK developments via licenses.

- In the 1980's and 90's a lot of effort was put in by DRA/DERA (later QinetiQ) and laboratories such as CRL (formerly Thorn EMI) on Ferroelectric Liquid Crystal Displays (FLCDs), but this technology was faced with strong competition from the incumbent LC technologies, particularly active matrix displays. Although it currently has a small market share, FLCD technology is beginning to emerge as a serious contender in microdisplays used in projection systems. A spin out from Scipher (formerly CRL), Micropix, is leading the way with a pilot production plant based in Edinburgh.

- Current world-wide research directions for 2-D displays are twofold: one is aimed at higher performance (resolution, video, colour) and lower cost for monitors, notebooks and TVs; the other is aimed at rugged, flexible, low power displays, strongly driven by the growing market need for portable, electronic devices, capable of displaying clear, full colour graphics and text. New generation mobile phones and The "Electronic Newspaper", are just two examples of the latter. These are highly competitive research arenas, but, again, the UK is playing a significant- and in some cases leading role.

- There are two major world-wide developments in plastic displays: Cambridge Display Technologies, CDT, a spin out from research at Cambridge University, is pioneering the development of Light Emitting Polymers, and has already signed up major licensees world-wide. A direct competitor to CDT's technology is Kodak's small molecule Organic Light Emitting Display (OLED) which is being developed by a number of organisations including Opsys, a spin out from Oxford University.

- Both LEP and OLED are emissive displays which produce their own light. This results in them consuming more power than a LCD with its backlight off, but less power than a LCD with its backlight on. Power consumption will be a key factor in determining future applications. Reflective LCDs may well prove satisfactory in markets that do not require a high quality image. Another key technical factor in organic displays is ensuring satisfactory device lifetime. Plastics are notoriously permeable to atmospheric moisture, which can poison LEP and OLED displays and degrade performance. Use of barrier layers such as thin hybrid organic/inorganic layers is, therefore, essential.

- Research at DERA on Zenithal Bistable Liquid Crystal Displays during the 1990s resulted in a spin out company from QinetiQ, ZBD Displays Ltd in 2000. ZBD technology has the advantage that the bistable nature of the device results in non volatility: Unlike conventional LCDs, the ZBD display retains information when the power is switched off. The ZBD device can also be readily aligned to the substrate and has the advantage of a cell thickness tolerance much better than conventional LCDs - important factors to be considered in manufacturability. The advantages of low power consumption and low cost will enhance applications of ZBD in products such as e-books, smart cards and Personal Digital Assistants, (PDAs), for example.

- The market opportunity for large area flat panel emissive displays is being addressed by a UK start up company, STL. Based on photoluminescent LCD technology from Cambridge University, the potential of "seamless" tiling of LC displays offers a low cost alternative to the new plasma displays currently becoming available. There is also increasing interest in photo-emissive displays based on carbon nanotubes as field emitters. Demonstration panels have already been fabricated using low-voltage phosphors.

- Three-D displays are attracting increasing attention for Visual Simulation. Computer Generated Hologram technology is being researched at QinetiQ in support of Holographic Imaging (a 50/50 Joint Venture with Ford of USA), to develop an interactive imaging system that will ultimately enable the rapid design of products such as automobiles, without the need for clay models. It will also be highly useful in displaying large datasets such as those found in geophysical analysis.

- Thus, in contrast to the early days of Liquid Crystals Displays, the strong research position in UK is now being exploited in spin off companies from both Universities and government-owned laboratories such as QinetiQ.

- The entrepreneurial spirit in Universities has been enabled by an increasing awareness of the importance of: market needs, Intellectual Property and exploitation issues, coupled with appropriate resources and mechanisms such as Science Parks and Commercial Departments to assist with technology transfer. In recent years Venture Capital (VC) money has also become available for technology start ups, although this is expected to be more difficult in the near future as a result of the current downturn in technology markets and the requirement for the successful start ups to be further nurtured with larger amounts of second - and third round funding.

- The recent relaxation of civil service constraints has enabled QinetiQ to exploit its technology in new ventures, using its IPR as equity alongside VC funding. As in the case of UK Universities, the availability of a nearby Science Park and the increased commercial awareness at all levels helped the ZBD start-up. The ZBD company recently completed a second round of funding.

UK Strengths

- High quality research teams.

- Strong Intellectual Property portfolio, the key to technology transfer.

- Historical strength in Displays has fostered and encouraged present day capability.

- Good awareness of commercial market needs underpins the high quality research.

- Improved Technology Transfer mechanisms and commercial expertise in Universities and laboratories such as QinetiQ

- New spin out companies from basic research capability

UK Weaknesses

- UK has no major indigenous display industry, only fledgling start-ups.
- Apart from investments made in TV manufacture, which is based on mature (CRT) technology, there has been no major inward investment in Display technology by foreign companies.
- UK has historically been a supplier of materials for LCDs, but this position has been undermined by internationalisation of the marketplace and the lack of device manufacture
- The UK Displays infrastructure is, therefore, weak and has to rely significantly on non-UK based sources.

Opportunities

- Despite being inextricably linked with cyclical behaviour, the IT& Electronics market has grown at an average annual rate of 15%, and there is a high demand for new display devices in the general field of IT, founded on an insatiable demand for information. The needs for low cost, low power, rugged, high contrast, full colour, 2-D displays provide major drivers for innovation.
- Links to major world-wide industries using key IPR, such as the licensing by CDT to Osram (GE) and QinetiQ's links to Ford.
- Three-D display devices are in their infancy, but provide a major market opportunity, initially in high value professional applications, but possibly in higher volume consumer products in the future.

Threats

- Any reduction in government funding for seedcorn research threatens the UK ability to invent and be leading innovators in Displays - (MoD is no longer a significant funder of Display technology, for example).
- Fledgling start up companies usually need several funding rounds before they are able to "take off" and control their own destiny. Although many might be currently regarded as indigenous to UK, having spun out of UK institutions, there is no guarantee that they will end up this way, despite their ambitions and technological success. Thus, the existence of an indigenous UK Display industry is continuously under threat.
- In a burgeoning market such as Displays there is inevitably strong competition. OLED technology is a prime example - Kodak, Sanyo, Pioneer, Sony, Toshiba, Samsung and LG are all believed to be investing in manufacture of OLED displays.

Comments and Recommendations

- Previous investment by government in high quality research teams yielded a number of new UK spin-out display companies during the recent technology boom. Improved commercial awareness has captured key IPR, which has been used as the basis for exploitation and technology transfer.

- However, the fledgling UK Displays industry hangs by a thread, amidst stern competition from abroad, and its future will depend on continued success in the marketplace and the ability to secure future investments for growth. Much of this will be determined by commercial and financial pressures, rather than by direct government intervention.

- However, government can continue to play a role in supporting creative research to generate the IPR for the next generation of display products.

- Continued government support for creating the infrastructure for innovation and technology transfer is also needed

6. Sensors and Microsystems

Market and Technology Trends

- The UK has major industrial and academic strengths in the field of sensors, with many companies actively making and selling products based upon leading-edge technology in their fields. The UK is internationally competitive in many areas such as optical sensors, pyroelectric thermal imaging and biosensors, and is also active in the field of actuator technologies, but not as advanced as Germany or Japan.

- Microsystems Technology (MST) continues to be funded aggressively in Europe, the US (by DARPA) and Japan. New centres for microengineering are continuing to be established outside the UK, most recently in Korea.

- Microsystems components have now shown a clear performance advantage over established technologies in a number of areas, particularly optics. Older MST fabrication technologies based on bulk micromachining of single crystal silicon and surface micromachining of polysilicon are now being rapidly overtaken by hybrid technologies based on deep reactive ion etching of bonded-silicon-on-insulator, due to the higher material quality and aspect ratio available by this method.

- Microengineering of III-V materials is developing rapidly, for applications such as tuneable vertical cavity surface emitting lasers. Work has been initiated on microengineering of "hard" materials such as silicon carbide and diamond, in several centres outside the UK.

- Major markets continue to include inertial sensors, other physical sensors, microfluidic devices, microanalytical devices, components for data storage (hard drives), and optical components. Most of these impact both the Civil and the Military sector.

- The most rapidly expanding market is currently optical components due to its ability to realise scalable optical cross-connects and adjustable components such as variable optical attenuators, tuneable filters and tuneable lasers. The strategic importance of the technology is highlighted by recent purchases of the OXC company Xros by Nortel for $3.25B, the tuneable laser company CoreTek by Nortel for £1.5B, the Cronos foundry (ex-MCNC) by JDS Uniphase for £750M, and the CAD developer and foundry Intellisense by Corning.

UK strengths

- There has been a rise in UK industrial interest in microsystems technology. The industry covers both large companies with a minor micromachining activity for specialised components, and SMEs with micromachined products that comprise a large part of turnover (Drucke).

- Within the UK there are significant military developments, such as gyros (BAESystems) and thermal imagers, both supported by QinetiQ, who have there own active programme.

- The UK telecommunications components sector (led by Nortel, Agilent, Bookham and the new start-up Kymata) expanded rapidly in 2000-1, encouraging microsystem technology.

- A Microsystems Manufacturing Association (MMA) has been launched, with support from UK Academic Institutions, led by IMechE.

- The UK academic base is consolidating. The following UK Universities have been identified as being active in MST: Bangor, Cambridge*, Cardiff, Cranfield*, Edinburgh, Glasgow, Heriot-Watt, Hull, Imperial*, Southampton*, Strathclyde, Surrey, Warwick* (where * denotes a major centre).

- Central Government support for microsystems technology has improved through the three funding rounds of the EPSRC Microsystems Technology Integration program, and the DTI LINK project.

Weaknesses

- Lack of strategic approach from government in steering the development of all these technologies has led to poor focus (In Scandinavia there are 5-year programmes focussed on centres of excellence in particular fields). DTI activity in the past consisted largely of fact-finding missions and roadshows for non-UK technology.

- UK Institutional interest in MST has reduced, due to the winding down of the relevant subcommittee S11 by IEE as part of their recent restructuring (although this is somewhat compensated for by the launch of the MMA).

Opportunities

- The world market is very large and growing (many $B), both for sensors in almost all products using electronics, and for actuators to go into "smart" systems, with a growing need for sensors in the military field, for biological sensors, and for fully integrated sensor systems with intelligence at the front end

- The DTI is currently assessing the possibility of part-funding a UK National Fabrication Facility in Microsystems.

- There is the possibility that a Faraday partnership in the area might get off the ground at the next round.

Threats

- US and European programmes on MEMS threaten to undermine more traditional approaches to sensors. The UK investment in technology is, relatively speaking, not strong in this field: The US has major programmes on optical sensors that the UK cannot match.

Recommendations

- The disruptive nature of microsystems technology is now established beyond reasonable doubt. Central Government strategy therefore now needs to move away from information gathering to a clear promotion of the technology, for example through The National Centre sector-based LINK programs.

- The UK government should establish themed and integrated programmes in particular areas of sensors and actuators, involving both industry, academic and government labs (along the lines of the "lab on a chip" programme. These should be industrially driven.

- Funding for academic programs should be increased.

- There is also a clear requirement for the introduction of MST as an academic discipline into higher education as part of a policy of improved training in new technologies. Establish a national strategy aimed at increasing the level of technical ability in the workforce through a nationally integrated and well funded education programme at all levels.

7. Nanotechnology

Market and Technology Trends

- Nanotechnology can broadly be defined as the manipulation of matter on the scale of less than 100nm in order to obtain useful properties and/or device characteristics. The term originated in the field of ultra-precision engineering and was applied to the machining of mechanical artefacts to this precision. It has since also been applied to a huge range of technologies ranging from semiconductor devices (e.g. quantum wells and ultra-fine line lithography to applications of scanning probe microscopies (SPM) to nanostructured materials and self-organising molecular systems.

- The terms "top-down" (TD) nanotechnology has become accepted as applying to the creation of artefacts by the incremental improvement of machining precision, or artefact definition using machining, lithographic or SPM techniques. The term "bottom-up" (BU) applies to the use of nanostructuring and self-assembly methods for nanoscale artefact creation.

- Nanotechnology is an "enabling technology" which can be spread across a huge range of applications, of which the electronic sector is only one, and so has no clearly defined market. Many areas of nanotechnology are currently being exploited in UK industry, from ultraprecision engineering to nanostructured powders.

- The applications of TD nanotechnology to the electronics sector is obvious. There are some interesting possibilities for the applications of BU nanotechnology, such as self-organising inorganic or biological nanosystems in the development of new generations of electronic devices. There is much debate as to whether such systems can deliver the regularity needed for conventional electronic devices.

- Although there tends to be some confusion in the minds of politicians and the public, the fields of Nanotechnology and Microsystems are clearly distinct, as most of the dimensions and tolerances in the latter are not in the nanoscale. However, there is a close relationship and growing overlap between the fields, for example in the development of specialist SPM tools. The area of Nano-Electro-Mechanical Systems (NEMS), which covers MEMS or MST devices with nanoscale dimensions is another.

- The applications of TD nanotechnology in electronics are clear. The creation of machines for silicon IC manufacture depends entirely on the ultra-precision mechanical engineering technologies in everything from silicon wafer grinding through to lithographic steppers. The applications of BU nanotechnology are less clear because the field is a lot younger.

UK Strengths

- The UK is particularly strong in the exploitation of TD nanotechnology, especially ultra-precision engineering. Cranfield University has played a leading role in this field and the company CPE (now part of Western Atlas) is a world leading developer and manufacturer of ultra-precision machine tools. The UK has also been quick to lead the way in developing many specialised uses of SPM.

- The UK has a strong intellectual position in both TD and BU nanotechnology, with many universities being recognised as internationally leading in their fields.

- The UK was one of the first nations to encourage nanotechnology, with both LINK and EPSRC programmes in the field. Ironically, these were completed in 1997, and no follow-on programmes were established, just as many other countries started to generate their own programmes, looking to the UK for their lead.

- The EPSRC has established networks in the area and has established coordinated programmes in nanotechnology through the establishment of two Interdisciplinary

Research Collaborations (IRC's) centred at Oxford and Cambridge. These started in 2001.

- The UK (Cranfield University) started and is leading the European Society for Precision Engineering and Nanotechnology (EuSPEN), funded under Framework IV. The Institute of Nanotechnology, based in the UK is taking a very positive role in promoting the field in the UK and putting together a European network on bottom-up nanotechnologies. The professional bodies (such as the IoM and the IEE) have committees set-up to promote the field in the areas they represent.

- The DTI has recognised the need for an initiative in the area and has established a number of studies to plan the best ways forward.

UK Weaknesses

- A tendency not to build on a lead when we have one, exemplified by the lack of a programme to follow the initial LINK and EPSRC programmes.

- Relatively poor collaboration between the universities, arising out of a strong level of competition for relatively poor levels of funding. This is improving as networks grow and the establishment of collaborative programmes through the IRC's will undoubtedly assist this.

Opportunities

- The opportunities for the exploitation of the successful and accurate manipulation of matter at this scale are huge.

- Framework 6 will have a major focus of nanotechnology.

Threats

- The USA has announced funding of $560M in the field, although this covers all nanoscale activities. There is no doubt that much of this is relabelling of existing funding, but it has put a focus on the topic that has stimulated action within DTI.

- Japan has a 10 year plan in the field.

Comments and Recommendations

- Continue to encourage the formation of industrial/academic networks in the UK.

- Promote the development of technologies exploiting the interface between BU and TD approaches to nanotechnology.

8. Non-Semiconductor Electronic Materials

Market and Technology Trends

- These materials include the wide range used in non-semiconductor electronic devices, including ferroelectrics, ferromagnetics and magnetostrictives. The first of these two satisfy the largest group of applications and have a very large market, with a significant amount of manufacturing and research capability within the UK.

- Ferroelectrics (polar dielectrics in which the direction of polarisation can be switched by the application of an electric field) offer a large range of useful properties, including: pyroelectric effects (used in uncooled infra-red detectors in devices ranging from people sensors through spectroscopic analysis equipment to thermal imaging); piezoelectric effects (used in sensors, actuators and frequency control/ filtering); high dielectric constants (used in multi-layer ceramic capacitors); strong electro-optic effects (used in light modulators and Q-switches); ferroelectric hysteresis (used in non-volatile memories) and, when in semiconductor form, anomalous temperature coefficients (used in motor protection devices and self stabilising space heaters).

- The world market for ferroelectric materials and devices is probably in the range $20-30Bn pa. The largest sectors here are currently based on ceramic materials such as derivatives of lead zirconate titanate (PZT) and barium strontium titanate. Other materials are, however, also of considerable importance, such as lithium niobate, lithium tantalate and lead magnesium niobate. The multilayer ceramic capacitor market alone is worth of the order of $10Bn pa. Piezoelectrics (in everything ranging from cheap sounders for alarms and cards worth a few pence each to highly sophisticated multi-element ultrasound arrays for medical imaging worth ca £1000 each) have a market also in this range.

- Many of these materials are of considerable importance in defence applications. Piezoelectrics are essential to sonar and weapon fusing. Pyroelectrics are offering new solutions to the problem of low cost thermal imaging for infantry use. Electro-optic materials are essential to laser targeting. The volumes of materials used here are small and the tendency for sonar is to rely on commercial materials procured to high specification. There is a possible vulnerability in the UK to the supply of specialised pyroelectric materials for uncooled thermal imaging.

- Superconductivity remains a minor research topic, but as a potential high-reward non-semiconductor electronic material technology it is and should continue to be funded within Universities. However, larger companies have greatly reduced their involvement with high-temperature superconductivity, particularly as far as electronic applications are concerned. Industrial interest is now focussed on small start-up companies, particularly in the US, although the UK is weak in this area. Much of the early work on material development has resulted in the availability of material as a commodity product in the case of wire and thin films for microwave applications. Thin film filters are a major focus for US start-up companies, and are undergoing field trials for the potentially large base-station market.

- Until recently, it would have been perceived that bulk ferroelectric materials were a reasonably mature technology. Most of the requirements for new materials and processes in the UK were being met by a relatively small number of companies and universities working in the topic. However, there have been developments in the

USA in the last few years in new piezoelectric single crystals (such as lead zinc niobate - lead titanate) which could revolutionize piezoelectric devices. These show extraordinarily high electromechanical coupling factors (ca 90%) and strains which will translate directly into improved bandwidths in medical ultrasound devices, and high efficiency in actuation. So far these are very expensive materials to produce, but ultimately this problem could be solved.

- A new company, The Crystal Consortium (TCC), was formed in 2000 by consolidating the bulk crystal growth capabilities of QinetiQ and the University of Strathclyde. In addition to the growth of bulk optical materials TCC will also develop the growth of new piezoelectric crystals.

- Ferroelectric thin films deposited directly on silicon offer new possibilities in microsystem devices and nanotechnology.

UK Strengths

- The UK has the strongest volume manufacturer of piezoelectric material in Europe (Morgan Matroc Electroceramics) who employ ca 500 people in the UK and are also a world player through their US subsidiary. It also has smaller, specialist manufacturers such as Advanced Ceramics Ltd. AVX (based in Coleraine, NI) is a subsidiary of Kyocera and is a volume manufacturer of multilayer ceramic capacitors. Oxley Developments is a specialist manufacturer of these components, mainly for military applications. Bowthorpe (part of Spirent) manufactures PTCR ceramics for current overprotection devices and sensors. These are used in automotive and medical applications. The total number of employees in the materials manufacturing sector of this industry in the UK is probably between 1000 and 2000.

- The strongest UK exploitation of superconductivity is by Oxford Instruments, primarily in magnet technology, although with a subsidiary business in quantum magnetometers for advanced instrumentation. This represents a major strength. QinetiQ have built a strong reputation in both active and passive devices, but have made a decision to stop the development of superconducting logic in view of the very long development times. There is a significant research in UK Universities, particularly Birmingham, Cambridge, Oxford and Strathclyde, in both theory and applications.

- The UK is strong in industrial users of ferroelectric materials, including piezoelectric ink jet printing (e.g. Domino, Xaar), medical ultrasound, industrial and aerospace precision actuators, uncooled pyroelectric devices (BAE SYSTEMS, IRISYS), integrated optic devices, sonar/NDE (Thales, Sonardyne), and microwave filters for base stations (Filtronic Comtec). A significant proportion of these are new SME’s who are exploiting the materials in new high technology products and experiencing rapid growth. Examples are Queensgate (recently bought by JDS Uniphase for ca £90M) and Xaar, which floated on the stockmarket last year. The value of the businesses in this part of the sector is certainly well over £10Bn, mostly based on solid manufacturing capability and a strong position in IPR.

- The UK has a strong intellectual position in the field of ferroelectric materials with several strong university groups, both in the field of basic materials, technology and devices/systems. Examples include Bath, Birmingham, Cambridge, Cranfield, Leeds, Manchester, Oxford, Sheffield, South Bank, Strathclyde, UCL, Warwick. Particular strengths in the university sector include ceramic materials processing, understanding of the basic properties of these materials, ferroelectric thin films and microsystems, ultrasound, pyroelectrics. The NPL is managing a programme on the characterisation of functional materials which is focussing on piezoelectrics.

UK Weaknesses

- Until recently, there was no UK research activity into the new piezoelectric crystal materials referred to above. An EPSRC project has been established (Leeds and Strathclyde) and can be supported by TCC.

- The general level of functional materials activity within EPSRC is small.

- There appears to be a shortage of scientists and engineers in the functional ceramics industry.

Opportunities

- There are new opportunities emerging in the high technology exploitation of ferroelectric materials, such as medical ultrasound and thermal sensing/imaging.

Threats

- The strong activity in the USA and Japan in piezoelectric single crystals (the USA is spending $35M over 4 years on the topic) promises to leave the UK well behind in an important new materials area, and in the exploitation of these materials in devices and systems. Areas of particular concern are medical ultrasound and high performance sonars, the latter a serious issue for naval applications. Crystals prepared in the USA and Japan are unlikely to be available to UK companies, even in the medium term, although TCC can reduce this threat.

Comments and Recommendations

- The issue of training in advanced functional materials needs to be addressed with appropriate post-graduate training courses.

- The MOD and EPSRC should consider instigating a jointly-funded UK research programme in the preparation and applications of new functional materials.

9. General Recommendations

- There is a clear need to establish within the UK a state-of-the-art semiconductor processing facility, providing advanced technology for the processing under production conditions of both silicon and III-V materials. The Centre will provide a facility for industrial development, prototyping and low-volume production, and also act as a major academic research resource. In addition to semiconductor materials, the Centre will provide for the processing of other materials such as those used for sensors and microsystems. The equipment must be such as to allow the Centre to participate fully in European programmes, particularly in view of the increased emphasis on large projects and networks in the next call. The cost of such a facility is approximately £100M, much less than for a high-volume silicon facility, and there is the clear expectation that this cost will be recovered through subsequent industrial exploitation within the UK.

- UK Universities should be encouraged to collaborate and co-ordinate their research programmes further, particularly when advanced and expensive facilities such as e-beam lithography or growth equipment is necessary. An example of the lack of collaboration is provided by III-V materials for device applications, where competition between Universities has led to fragmentation and lack of focus of the research effort. The role of Central Facilities such as RAL, Sheffield and Southampton should be examined with a view to improving collaboration.

- Activities such as MST and sensors should continue to be funded within Universities as at present through responsive and managed programmes. Processing would be carried out in collaboration with the Semiconductor Research Centre, bridging the gap between initial demonstration within Universities, and full-scale production where industry owns and controls all the processing equipment. The use of the Centre will ensure that processes developed within Universities are compatible with large volume production.

- The need for trained personnel is a continuing theme in all areas of electronic materials. The recent increase in PhD salaries should help, but there is a need to increase the salaries of research associates. Concerns over increased levels of debt resulting from the introduction of four-year courses and tuition fees makes both Research Studentships and RA positions much less attractive, and MSc courses within the UK now have more than 70% overseas students.

- There are encouraging signs that there is an increasingly entrepreneurial approach to technology development, as demonstrated by spin-outs from QinetiQ, Glasgow and other Universities. Small company schemes should be enhanced to increase the success of these companies making it through the initial stages.

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