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CIKC CAMBRIDGE INTEGRATED KNOWLEDGE CENTRE
Advanced Manufacturing Technologies for Photonics and Electronics –
Exploiting Molecular and Macromolecular Materials

UNIVERSITY OF CAMBRIDGE

Funding Breakthrough Technology

CIKC Final Report

Samantha Sharpe, Andy Cosh & David Connell

Executive summary

This research investigates the commercialisation of breakthrough technologies from science base to viable commercial applications. Breakthrough technologies emerge from novel and discontinuous innovations that result in significant and irreversible changes. These innovations are based on new, under-or un-exploited physical, chemical and biological phenomena, that allow order of magnitude improvements in the performance of existing products and/ or the creation of entirely new ones. These novel innovations may entail the development of 'new technology platforms' with applications across a range of products and markets. Many of the resultant applications are not envisaged at the time of the initial innovation.

This report summarises results from seven historical case studies of breakthrough technology development. The case study technologies are Liquid Crystal Displays (LCD), Light Emitting Diodes (LEDs), Optical Fibres, Photovoltaics, Inkjet Printing, Giant Magnetoresistance (GMR) and Microelectronic Mechanical Systems (MEMS). The case studies illustrate the dramatic changes breakthrough technologies can make on the industrial landscape and the context surrounding discovery and commercialisation of these technologies. The potential for extensive industrial development; enhanced national competitiveness; and employment and export growth are the key motivators for government activity in breakthrough technology development. These upside gains can outweigh the downside risks of commercialising these technologies and the knowledge that most of these attempts at breakthrough technologies will come to nothing.

Public policy in recent decades has attempted to encourage the discovery of breakthrough technologies and accelerate the commercialisation of these technologies. In the UK the long-term experience of and attitude towards science-based commercialisation has not been successful. It would appear that the UK has strengths in the production of (for want of a better term) ‘basic science’, but poorly executes on the commercialisation of this basic science into technology and applications.

The research addressed three questions;

1. How do commercialisation patterns emerge for breakthrough technologies?
2. What are the key factors/ inflection points in these commercialisation patterns for breakthrough technologies - both successful and unsuccessful commercialisations?
3. How does the UK perform in the commercialisation of breakthrough technologies?

How do commercialisation patterns emerge for breakthrough technologies?

The commercialisation patterns of breakthrough technologies are best illustrated by what Adner and Levinthal (2002) refer to as speciation events. In that progress is cumulative and slow up to a certain point of discovery or breakthrough when dramatic and quick evolutionary change takes place and sees the emergence of a new technology with new potential applications, markets and industrial direction.

The evolutionary approach highlights three further characteristics of breakthrough technology commercialisation; the process involves long time lines; breakthrough technologies are comparatively rare events; breakthrough technologies have the ability to cause dramatic changes in the industrial landscape.

What are the key factors in these commercialisation patterns?

This report identified two transition periods in the commercialisation of science-based technology; the transition from science-base to pre-commercial environment, and the transition from pre-commercial to commercial environment. Factors that drive technology from the science base to the pre-commercial environment include interdisciplinary interaction, time (often decades), a background of 'blue skies' or curiosity-driven research activity that is sheltered from the business cycle, technology champions that spread the word of the potential applications and luck. Luck that the right people will meet at the right time and that certain research will be supported at the right time (although there are many examples of firms making their own luck as well).

Factors that see a breakthrough technology transfer from the pre-commercial environment into the commercial environment include the development of niche applications for/ and the existence of non-price sensitive customers. These early applications build the reputation of the new technology and non-price sensitive customers allow engineering and manufacturing techniques to be developed in an environment where unit cost is not the primary consideration. Another key factor in transferring breakthrough technology from the pre-commercial environment is corporate strategy.

Firms (mainly large firms) make numerous strategic decisions in the provision of resources to new technologies in the pre-commercial phase. Strategic areas include decision and position of market entry; creating internal capability in technology or cultivating external links; decision to cannibalise existing products with new technology; vehicle of commercialisation (start-up, spin-out or corporate unit); and mechanisms for funding technology development through pursuit of R&D contracts, participation in R&D programs (usually cooperative), internal revenue or external sources such as ‘money clubs’[1] and risk capital.

How does the UK perform?

Assessing the performance of the UK in science-based commercialisation is difficult. Breakthrough technology development is a global phenomenon involving actors from many countries even just in the cases examined in this project. The case studies highlight numerous examples of UK participation; in particular UK organizations played a major role in the commercialisation of liquid crystal displays, optical fibres, light emitting diodes (particularly organic light emitting diodes) and continuous inkjet printing (CIJ). The UK continues to show technology leadership in CIJ and emerging elements of the LCD industry (for example Zenithal Bi-stable LCDs) and the LED industry (continuing in organic LEDs).

Three conclusions are drawn from the case study analysis of UK performance in the commercialisation of breakthrough technology. Firstly, the context of national programs of research in breakthrough technologies has a strong influence on the eventual commercial outcomes of the research. Secondly, the type and resources of organizations hosting pre-commercial development impact on the ability of the technology to transfer successfully to the commercial environment. Organizations’ need both pre-commercial and commercial technology development ability and resources, or the ability to transfer the technology from one organization to another in order to provide this ability and resources.

Thirdly, breakthrough technology, because of its long timelines of development and potentially revolutionary industrial effects, will be influenced by macroeconomic, social and political factors in expected and unexpected ways. This means that policy activity aimed at accelerating technology commercialisation will have to be long term but, be pro-active in some circumstances and responsive in others. Such a need for flexibility in policy will require ongoing two way communication between the policy, industrial and scientific communities.

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[1] We use this term to refer to funding arrangements that include subscriptions or annual payments made by firms (usually potential customers and suppliers) to other firm/s to fund technology development.

Policy implications

The aim of this research is to understand the process of commercialisation of breakthrough technologies from the science base to viable commercial applications, through the lens of how this process is funded. This research contributes to the commercialisation activities of the Cambridge Integrated Knowledge Centre (CIKC) by providing evidence and informing commercialisation trajectories of past breakthrough technologies. It is to this aim that policy implications are highlighted in the following seven areas:

1. The importance of multi-disciplinary teams working in close proximity
2. The role of 'mission driven' environments that support both pre-commercial and commercial technology development
3. Importance of government R&D contracts for early development work, particularly the US SBIR programme
4. Public procurement as a 'deep-pocketed' and first customers for breakthrough technology
5. Limits and role of current venture capital model in supporting new technology commercialisation
6. Potential for the new Strategic Investment Fund to provide an alternative source of technology funding
7. The role government policy in areas such as space, energy and defence plays on innovation activity and the need for such policy areas to be integrated into a wider view of innovation policy.

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1. Introduction

'The race is not to the swift, nor the battle to the strong, neither yet bread to the wise, nor yet riches to men of understanding, nor yet favour to men of skill; but time and chance happeneth to them all.' Ecclesiastes 9:11 Quoted by George Heilmeier in his acceptance speech on receiving an award for his pioneering work in LCDs, Tokyo, 1990 (Johnstone 1999, p.88)

The commercialisation of breakthrough technology is a rare event, yet when it does occur it can have dramatic effects on the industrial landscape. When and where the next breakthrough technology will emerge is difficult to predict because the extent and reach of the disruptive capacity of a new scientific discovery is unknown, as is the range of applications that such a discovery can change or create.

Breakthrough technologies emerge from novel and discontinuous innovations that result in significant and irreversible changes. These innovations are based on new, under-or un-exploited physical, chemical and biological phenomena, that allow order of magnitude improvements in the performance of existing products and/ or the creation of entirely new ones. These novel innovations may entail the development of 'new technology platforms' with applications across a range of products and markets. Many of the resultant applications are not envisaged at the time of the initial innovation.

Public policy in recent decades has attempted to encourage the *discovery* of breakthrough technologies and *accelerate* the commercialisation of these technologies. Government's may have invested heavily in the science behind these technologies; through the training of the highly skilled staff that work in both public and private research and development labs; through the provision of subsidies and grants to encourage R&D activity; and the use of public procurement, where the government acts as the first key customer.

This public policy interest in following and trying to support these technology activities lies in their enormous potential for value creation across a broad range of industries and applications (Maine and Garnsey 2006). New industries can create new employment, new export incomes and increase individual country's international competitiveness. These upside gains of income and employment can outweigh the downside risks of commercialising breakthrough technology and the knowledge that most of these attempts at breakthrough technologies will come to nothing.

This report summarises results from seven historical case studies of breakthrough technology development. These case studies illustrate the dramatic changes breakthrough technologies can make on the industrial landscape and the context surrounding discovery and commercialisation of these technologies. The analysis of the emergence and development of breakthrough technologies encompasses the three inter-related areas;

> *Scientific discovery* - the processes, people and organisations involved in the discovery of new, under or unexploited physical, chemical and biological phenomena.
>
> *Pre-commercial environment* – where the science transfers into technology applications. The scientific discovery may have highlighted potentials for performance improvements of current technologies and/ or new technology platforms; understanding how these applications are identified and progressed is critical.
>
> *Commercial environment* - the commercialisation of breakthrough technology particularly into brand new applications requires significant market development as well as the creation of suitable business models for exploitation. Commercialisation also requires the development of manufacturing capability to scale up production of the developed technology. All of these activities require successive cycles of innovation and have long timelines.

1.1 Research objectives

This research is part of the commercialisation stream of the Cambridge Integrated Knowledge Centre (CIKC). The CIKC brings together research, development and commercialisation activities in Photonics and Electronics at the University of Cambridge. The project contributes to the commercialisation activities by providing evidence and informing commercialisation trajectories of past breakthrough technologies. This will allow us to interpret the current advances in Photonics and Electronics within the recent history of breakthrough technology emergence.

The aim of this research is to understand the process of commercialisation from science base to viable commercial applications, through the lens of how this process is funded. The focus on financing allows specific commentary and advice on key factors in commercialisation patterns and the role of finance and financers in this process, to be provided.

The research questions are:

1. How do commercialisation patterns emerge for breakthrough technologies?
2. What are the key factors/ inflection points in these commercialisation patterns for breakthrough technologies - both successful and unsuccessful commercialisations?
3. How does the UK perform in the commercialisation of breakthrough technologies?

This work builds on previous research investigating the financing of new high-technology firms (NTBFs) (Sharpe, Cosh et al. 2009b). The previous research analysed the financial pathways and external fundraising experience of NTBFs and identified four funding typologies of these firms. This research will expand the area of analysis to include the broader innovation to market pathway of a specific set of science-based breakthrough technologies.

2. Literature review

The commercialisation of technology from the science base is considered one of the key drivers of economic growth. This view is based on a combination of the recent US experience in high technology development and commercialisation (Hughes 1998; Chandler 2001; Kressel and Lento 2007) and evidence of large upscale profits achieved by successfully commercialising discontinuous innovations (Maine and Garnsey 2006). Successful commercialisation of science-based breakthrough technology can also have significant impacts on the national competitiveness of countries involved. The economic prowess of the US has been attributed to their success in developing high technology industries over the last five decades of the twentieth century (Nelson 1990)[2].

2.1 Defining breakthrough technologies

In this research we define ‘breakthrough technology’, as;

Novel and discontinuous innovations that result in significant and irreversible changes and are based on new, under or unexploited physical, chemical and biological phenomena, that allow order of magnitude improvements in the performance of existing products and/ or the creation of entirely new ones. Breakthrough technologies may entail the development of 'new technology platforms' with applications across a range of products and markets.

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[2] Nelson cites three reasons behind US technological leadership, i) increased higher education participation, ii) increased scientific research in universities, supported by the establishment of public grant administrating organizations; the National Science Foundation and the National Institutes of Health, plus large scale funding by government departments, particularly the Department of Defense (DoD), the Atomic Energy Commission and NASA, iii) and finally the rise of corporate R&D. Corporate R&D was also supported by DoD and NASA, but by the mid 1960, 50% of corporate R&D was privately funded (Nelson 1990).

This definition builds on, and encompasses a number of other terms that are used, often interchangeably, in the innovation and high technology management literature including; radical technology (Peters et al), radical innovation (Ettlie, Bridges et al. 1984; Utterback 1996; Grover, Purvis et al. 2007), architectural innovation (Abernathy and Clark 1985), disruptive technology (Christensen, Johnson et al. 2002; Kassicieh, Kirchhoff et al. 2002; Minshall, Seldon et al. 2007), non-incremental technical change (Freeman and Soete 1997; Nemet 2009), emerging technologies (Adner and Levinthal 2002), generic technology (Maine and Garnsey 2006) and revolutionary innovation (Kressel and Lento 2007). Although there are differences between these various terms, particularly in the time and circumstances of their use, the purpose of this brief overview is not to discuss the merits or contributions of each (see (Linton 2009) for a good overview of innovation terms), but to highlight consistent themes between all of these terms. The themes of irreversible change, new phenomena and the potential for radical and/or new industrial creation are encompassed by the majority of these terms. In this sense we believe that the definition used for this research offers adequate coverage of these themes.

This research looks at breakthrough technologies that are sourced from the science base. This adds another layer of complexity to the commercialisation process. The vast majority of technologies can trace their roots to research in science, somehow and sometime. It is therefore important to distinguish what we mean by science based commercialisation.

Science-based commercialisation refers to the development of new to market technologies based on new scientific discoveries. The complexity of this process arises through a series of ‘unknowns’- how and when these discoveries will transfer into applications is unknown (Pavitt 1991) as is how they will change industrial composition and competitiveness (Tijssen 2002)and who will benefit from any resulting wealth creation (Kassicieh, Walsh et al. 2000). The functions and advantages of new science-based applications are unfamiliar to customers (Freeman and Soete 1997). Market feedback in the early stages of science based commercialisation is not available to guide the commercialisation process in the same way as exhibited in other areas of new product and service development. This can result in mismatched technology and market development.

The dichotomy between 'technology push' and 'market pull' is often used to highlights these differences. The emergence of technology via the ‘technology push’ pathway begins with scientific inquiry into specific phenomena. This in turn leads to speculative R&D work and potentially technological innovation. Market search then becomes the focus. In the 'market pull' version of technology development the process begins with a relatively well defined technological need. R&D focused on developing applications to meet this need occurs and the resultant technological innovation, already with established market orientation, is commercialised into marketable applications. This is a simplified version of technology development, and the ‘technology push’ and ‘market pull’ pathways represent opposing ends of a spectrum of activity rather than two categories into which all technologies must fit. The pathways do however highlight different challenges facing technologies as they track to market.

The science-based technology breakthroughs investigated in this research fall more on the 'technology push' side of the spectrum in their initially stages of development. This is not to say that all emergent applications of these technologies will remain 'technology push'. In many cases they will be market driven. One of the tenents of the CIKC program is to more closely align the scientific-inquiry driven technology 'push' pathway with the market oriented ‘pull’ pathway.

The technologies discussed in this report are the result of development and engineering throughout a long period of pre-commercial development. The multi-varied paths of development that these technologies take can create the situation where “the greatest benefits are the least anticipated and surface many years later” (Tijssen 2002 p.509). Science based commercialisation success can be incidental and emerge from largely inconsequential (at the time) activities by a number of actors in the very early stages of the breakthrough technology's evolution - activities that are taken when the end result and any resulting profitable industry is a long way off. This is why understanding previous science based commercialisation, particularly the decision making processes involved for firms and other organisations about where and in what situations science is commercialised and the progress from science to technology application, is critical to inform future decision making.

The pathway of science based commercialisation includes three areas; the science base, the pre-commercial environment and the commercial environment. The points of transition between these three areas of activity provide the most illustrative units of analysis, so the movement of technology from the science base into the pre-commercial environment, and then from the pre-commercial environment to the commercial environment. This is illustrated in Figure1. The figure shows the pathway from the science base to the commercial technology environment. This pathway is intersected by a period of pre-commercial development, with the intersection points highlighting when technologies move into pre-commercial development and when they move out of this phase.

The pre-commercial environment therefore is a critical junction in understanding the development of breakthrough technology.

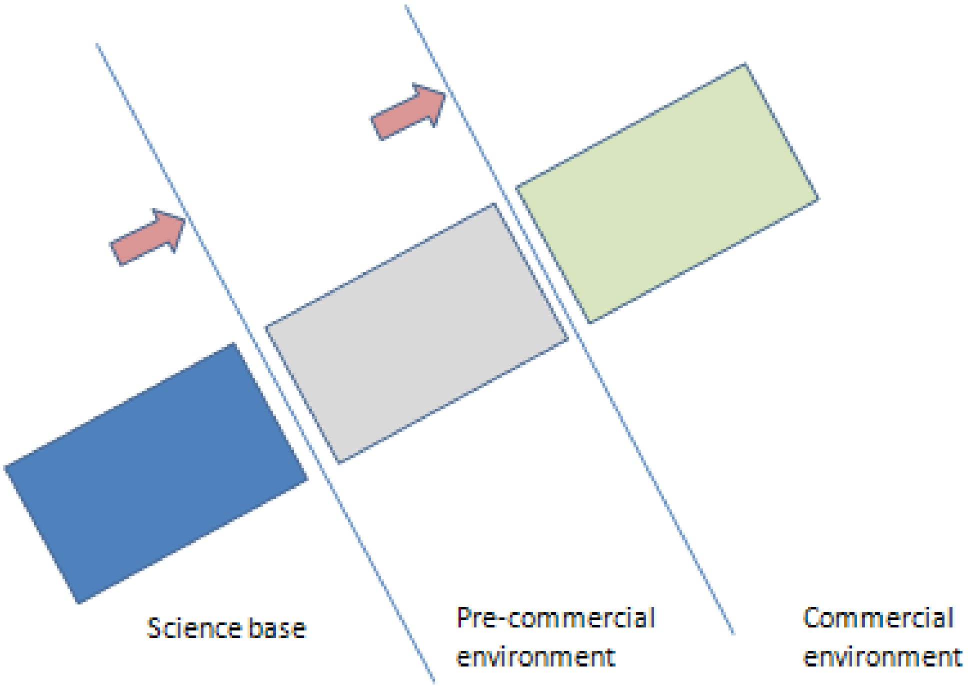

Figure 1 Technology emergence from the lab to the market

Adner and Levinthal (2002) use the analogy of 'speciation events[3]' as used in evolutionary biology to understand this stop-start relationship in emerging technology commercialisation. They note technology evolution can either be a quick process with the new technology rapidly linked to applications (and demand for applications) or, be a long and slow process.

The two transition points can occur in two places (geographically) and at different times, (sometimes decades can elapse between the transition from science base to pre-commercial environment and then pre-commercial to commercial environment) for each application. The transitions also each require different sets of decision making and actors. The transfer to the commercial environment is heavily dependent on the resources available at that point of time (knowledge, financial,

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[3] Adner and Levinthal (2002) define speciation events as the separation of one evolving population from its antecedent population, which in turn allows subsequent populations to follow different evolutionary paths.

organisational and market) and the progress of other technological advances commercialising or being developed at the same time. Finally, the transition points are independent of each other, just because a technology transfers from the science base to the pre-commercial environment does not mean that a transition to the commercial environment will also necessarily occur.

2.2 Funding technology emergence

Commercialising breakthrough technology has demanding funding requirements. Funding needs to cover not only extensive periods of R&D but also market exploration and business development. Financial support for the commercialisation of breakthrough technologies is accessed from three main sources; Government, through research programs and grants; large firms, through their research and development programs; and thirdly various forms of external and risk capital. Increasingly, in recent times we can add a fourth category, small and medium sized firms funding technological development through revenue from R&D contracts for other customer firms (usually large firms).

The commercialisation process for most breakthrough technologies will access all of these. Yet as technologies develop, and specific applications emerge the composition of funding sources moves from public to private. The public good aspects of ‘exploratory’ or ‘basic research’ see public funds supporting the basic science period, private funding supports the majority of commercial environment development. The pre-commercial environment draws on different mixtures of public and private funding sources. The combination of funding sources leaves gaps in funding for some areas of development. This research investigates these changes in composition of funding and the associated risk and reward profile through the commercialisation process.

2.3 The role of public policy

Public policy over the preceding decades has attempted to encourage the discovery of breakthrough technologies and accelerate the commercialisation of these technologies. The public policy interest in supporting these technology activities is in the potential for industrial development. New technologies can create new industries or reinvigorate mature ones. These new industries can have effects on export income and international competitiveness and increase knowledge based employment.

There are compelling reasons for investing in science and technology research, Nelson (1990) attributes US technological leadership for the majority of the last century to their increased investment in science and engineering either through higher education participation, university research or corporate R&D. Yet because of the long gestation period of many science-based technologies, particularly breakthrough technologies the rewards for such technological investments do not always accrue to those who make the investments.

Public policy has a role to play in every step of the science based commercialisation pathway. In the science base, public funds are the primary source for curiosity-driven and basic scientific research. In the pre-commercial phase public institutions, either government R&D labs or universities play a role in the research and development activities that support the continuing technology development. The funding mechanisms used by organisations in the pre-commercial environment are broader than in the basic research arena; they still include funding for Universities to carry out research but also include specific focused government funding programs, government R&D contracts for the development of specific types of technological applications. Also important are access to government scientific agencies and scientific equipment to test and measure new technologies (important in setting standards and establishing the credibility of competitive advantage of a technology with competing technologies), and government procurement and contracts which make government departments first customers for new technology applications.

Public policy interventions have focused on this pre-commercial environment, and activities that assist technology transition from the pre-commercial to the commercial environment. This is particularly evident in the past few decades. This has been done in a number of ways including, encouraging universities to patent, license and commercialise science based discoveries that emerge from their research. Other countries such as Germany and the Netherlands have developed intermediate institutions that offer an incubation space between universities and industry. In the US the *Small Business Innovation Research (SBIR)* programme has used government procurement funding to offer 100% upfront development funding for technology applications that can address government stated needs, therefore providing funding but also demand pull for any emergent technological application (Connell 2006). Other countries have sought to increase subsidies available to firms to invest in R&D, and subsidies to firms and individuals to invest in risk based investment opportunities - which are typically new technology based firms.

2.4 Research context

The value creation associated with the successful commercialisation of breakthrough technology means that analysis of commercialisation process is of immense interest both to governments and firms. In the UK the long-term experience of and attitude towards science-based commercialisation has not been successful. It would appear that the UK has strengths in the production of (for want of a better term) ‘basic science’, but poorly executes on the commercialisation of this basic science into technology and applications. Two quotes displayed below, separated in time by over 80 years, sum up the prevalence and long held nature of these views;

> *"These works reveal numerous cases in which members of the small band of British scientific men have made revolutionary discoveries in science; but yet the chief fruits of their work have been reaped by businesses in Germany and other countries..."*
> *Alfred Marshall, Industry and Trade 1919, p.102*

> *"The UK has a strong science base but lags in patenting and commercialisation..."*
> *Michael Porter and Christian Ketels, DTI Economics Paper No. 3 2003*

National performance in terms of science-based commercialisation is difficult to capture in a quantitative way. The global nature of many large firms, who are at the forefront of commercialising such technologies, makes this a difficult story to unpack at the national level. This is one of the reasons why the technology focused case study methodology employed in this project is useful.

2.5 Historical case study methodology

This research uses a historical case study methodology. Earlier sections of this report have alluded to the advantages of this approach including the ability to deal with the complexity of analysis of technological development; the many participants, organisations and geographies. Also, historical analysis allows us to deal with the long timelines involved in technology commercialisation.

Historical analysis of past technology commercialisation also has relevance to current considerations of science commercialisation. As Tosh (1984) points out, "...we know that we cannot understand a situation in life without some perception of where it fits into a continuing process, or whether it has happened before...our sense of what is practicable in the future is formed by an awareness of what has happened - or not happened - in the past" (p.1).

Although the historical method allows comparisons to be drawn between the different development paths of breakthrough technologies and the role of different actors, organisations and government policies in these development paths, it is limited to describing and analysing what happened (or did not happen), not what could have happened if situations were different(NRC 1999). The method also has the advantage of hindsight. A further limitation is that the economic, commercial and institutional environment has changed since our earlier cases.

In order to identify a group of technologies for the case studies a small questionnaire was circulated among the CIKC technology and advisory board members and technology project investigators. The questionnaire asked participants to nominate technologies they considered to be breakthrough technologies in two time periods; 1950-1980, and 1980 onwards. The questionnaire yielded 17 technologies (with multiple participants selecting the same technologies).

Case study selection

This list of 17 technologies was further refined down to the 7 technologies selected for the project. The refinements were made using the count of technologies nominated (whether multiple people nominated the same technology), spread of technologies across the two time periods (responses were dominated by technologies in the early time period) and then desk based research to identify a coherent group of technologies for analysis. We recognise this case selection method favours technologies in the materials sciences and physics fields because of the interests and expertise of the scientists and researchers we asked to nominate cases. However, the selection method allowed us to work on a group of cases with some technical coherence and also relationship with the current technological work of the CIKC. It also allows us to talk with more depth about the specific materials science commercialisation process.

A brief overview of the seven selected technologies is presented in Figure 4. Copies of the full case study reports on each of the investigated technologies can be accessed at http://www.cbr.cam.ac.uk/research/programme1/project1-24.htm

Figure 4 - List of the selected technologies and brief outlines

Technology	Brief outline
Liquid Crystal Displays	Liquid crystals were discovered in 1888 but not connected with display applications until the early 1960s. Early applications include pocket calculator and digital watch displays. Later applications including televisions and laptops had to wait for complementary innovations in thin film transistors and LC materials to become viable. LCD outsold CRT televisions for the first time only in 2007.
Fibre optic communications	Using transparent fibres to transmit light goes back to the Victorian era. A key issue was light loss and this was not resolved until cladded fibres were developed in the 1950s and 1960s. Fibre optics as a

	communications medium was first seriously suggested in 1966 with a paper by Kao and Hockman from STL that determined light loss needed to decline to 20dB per km for communications applications. Successive waves of innovation in optical fibres, and complementary technologies such as the laser saw optical communication emerge in twenty years (1960s-1980s). The development of erbium doped fibre amplifiers in 1989 by University of Southampton and Bell Labs allowed greater and greater amounts of data to be transmitted and accelerated the expansion of the internet age.
LEDs	The case study covers the development of traditional LEDs, Organic LEDs and GaN LEDs. LEDs are semiconductor devices that emit light when a diode is switched on. The various generations of LEDs can be differentiated by the different materials used in the active layer of the diode. Traditional LEDs trace their history back the early 1900s, but again the 1950s saw acceleration in the technology that led to applications. Further developments using different materials continued over the next few decades. OLEDs developed out of work in the 1970s on conductive polymers, with two types of OLED adapted to applications, the small molecule LED (SMOLED) and polymer LED (P-OLED). Emerging research on GaN LEDs can trace back to the 1960s, but the 1993 development of a viable blue GaN-based LED has focused the recent years of research. GaN LEDs and many applications of OLEDs are still emerging.
Giant Magnetoresistance (GMR)	Giant magnetoresistance was discovered in 1988 by two independent groups of European researchers. They found unexpectedly large changes in the electrical resistance of thin layered metal materials in response to a small magnetic field. The discovery represented a new physics phenomenon and led to applications in hard disk memory storage (IBM), progress towards MRAM (Magnetic Random Access Memory) and a new field of electronics, Spintronics (electrical devices that rely on electron spin for their power source). These latter two fields of applications are still in development.
Micro Electronic Mechanical Systems (MEMS)	The basis for microelectronic mechanical systems is the ability to create controllable, mechanical, moveable structures using IC (Integrated Circuit) processing technology. MEMS can trace their development back to the discovery of piezoresistivity at Bell Labs in 1954. Early applications for MEMS were very expensive and used initially only in space and aerospace with pressure sensors the primary application. The 1990s marked a period of acceleration in MEMS development. MEMS sensors for airbag systems in vehicles were launched n 1991. Micromachined components for ink jet printing cartridge nozzles were also released in the same time period. Intense investment in R&D in MEMS for optical, biomedical and consumer electronics followed. We are now seeing the beginning of mass integration of MEMS devices in consumer electronics.
Inkjet printing technology	Digital inkjet printing is a binary, non-impact dot-matrix printing technology. In its purest form inkjet printing is the jetting of individual ink droplets from a small aperture directly into a specified position on any manner of substrate. The concept of a printer that controls the flow of ink through tiny tubes dates back to the nineteenth century, but again the period of the 1950s saw the transformation of this concept into printing applications, first through a drive to automate biological analysis and then other demands of industrial printing. Inkjet printing divided into two field in the 1970s, the drop-on-demand method (which is exhibited in all

	modern desktop inkjet printers) and Continuous Inkjet (CIJ) (where the market is focused on industrial applications and more fragmented that the DoD market).Continuous Inkjet printing is a central focus for a number of firms in Cambridge who can all trace their lineage in technology and human resources back to Cambridge Consultants and R&D contract work completed by CCL for ICI in the 1970s.
Photovoltaics	A photovoltaic cell is a device that converts sunlight directly into electricity via the photovoltaic effect, where photons of sunlight knock loose electrons and induce current flow in the cell. Photovoltaic cells are generally classified into three generations. The first generation used single and poly-crystalline wafer based silicon cells and development was spurred on by the space age and the need for a reliable power supply for satellites. Second generation cells were thin film cells using materials such as cadmium telluride, cooper indium gallium selenide, amorphous silicon and micromorphous silicon. These cells were aimed at the terrestrial market, but cost reductions in material came at the price of cell conversion efficiency. Third generation thin film cells which are still in development attempt to keep costs savings of thin-film cells but increase conversion efficiency through new mechanisms such as up-conversion and tandem conversion, and utilizing nanocrystal and organic materials.

3. Case study analysis

The case study analysis is divided into three sections, a section for each of the three phases of breakthrough technology development; science base, pre-commercial environment and commercial environment. The science base is primarily concerned with discovery, the pre-commercial environment with the activities around establishing the potential of the technology, and the commercial environment on executing on this potential. These three phases cannot be seen as rigid categories as elements of each of these phases is present in the other; the process of discovery is ongoing in all of the phases, and establishing the reputation and potential of a technology occurs in both the pre-commercial and commercial environments. The characteristics discussed in the following sections are highlighted because they are dominant in their particular commercialisation phase.

3.1 Science base

With all the discoveries analysed in this research a number of themes of scientific discovery emerged.

3.1.1 Cumulative nature of scientific knowledge

Firstly, the cumulative nature of scientific knowledge development is evident in the initial stages of breakthrough technologies analysed in the case studies. All of these breakthrough technologies could trace their lineage back many years, often centuries to scientific advances developed long before. Liquid crystals were discovered in 1888, the photovoltaic effect was discovered in 1839 and the magnetoresistance effect (behind giant magnetoresistance) and the peizoresistive effect in metals (basis for MEMS) go back to Lord Kelvin (William Thomson) in 1850s.

3.1.2 Multidisciplinary research and co-located researchers

The breakthrough technologies analysed in the cases emerged through the contact of different disciplines in the form of multi-disciplinary research teams, or contacts between scientists of different disciplines within large R&D labs, or through specialised conferences. The effects of multidisciplinarity was evident both in the creation of formal multidisciplinary teams on specific research projects, but also through chance informal contacts between colleagues of different fields co-located within the same institutions.

Interdisciplinary research was considered a new concept. Until the early 1950s R&D had usually progressed through fields of research, rather than interdisciplinary teams. The Manhattan project (US effort to develop and build the first nuclear weapons during the second world war) has been referred to as “the first time that physicists, chemists and engineers worked together for a common goal” (Castellano 2005 p.9). Multidisciplinary research was not necessarily a goal of organisations involved in science based commercialisation, but rather a result of problem-based research agendas.

All the technologies analysed for this research benefited from this inter-disciplinarity. In LCD the interactivity between organic chemists, physicists and electrical engineering led to the creation of displays; in fibre optics it was the interplay between optics, physics, electronics and speciality glass fabrication that lead to the development of fibre optic communications. In the development of photovoltaics Daryl Chapin of Bell labs was initially trying to create dry cell batteries using selenium. He discussed the problem with his friend and colleague at Bell, Gerald Pearson (who was working on solid state silicon devices), who in turn discussed the problem with his colleague chemist Calvin Fuller. Fuller suggested that the problem may be overcome by using silicon doped with gallium in a hot lithium bath would produce more effective electricity generation. These discussions led to experiments and the development of a prototype which in 1952, was the most efficient solar cell, five times more efficient in solar to electricity conversion than anything that had been developed before (Perlin 2004).

The industrial research and development of the US in the post WWII period was a watermark period in the history of micro electronics – during this period the silicon chip was created along with a host of other micro-electronic development that were the predecessors of many technologies that are ubiquitous to us today. The major labs were AT&Ts Bell labs ("undisputedly top of the ladder"(Johnstone 1999), RCA's Sarnoff Centre, and the R&D labs of major corporates such as Westinghouse, GE, Texas Instruments and International Business Machines (IBM).

Similar corporate laboratories existed in Europe, Standard Telecommunications Labs (STL) and GTE Laboratories in the UK, Thompson CSF (France), Hoffman La Roche (Switzerland), and Siemens Aktiengesellschaft (Germany), and Sharp Corporation, Canon, NEC and Fujitsu in Japan. National research laboratories also played a part. These laboratories were usually linked to national military, energy or space departments (for example, Department of Defence and NASA in the US, Royal Signals and Radar Establishment (RSRE) in the UK, Commissariat a L'Energie Atomique in France).

Despite the much heralded decline in corporate R&D programs globally and the shift to 'open' innovation sourcing (which sees major corporates look externally to universities and SMEs for innovations rather than developing all innovations in-house (Chesbrough 2003)), in the case of GMR, the most recent breakthrough technology case study, corporate labs (IBM in this case) still played a pivotal role in engineering and developing the newly discovered giant magnetoresistance effect[4]. The post WWII era of investment in science and technology by both firms and governments; the military-industrial-university complex (Hughes 1998), exhibited most definitively by the US in the 1950s and 1960s, has no doubt generated many more technological advances than would otherwise have occurred. Whether the current systems of military-industrial-university complex can maintain the flow of technological advances is unknown, the long timelines involved means we will need to wait a few more decades.

3.1.3 Blue skies research – space for curiosity driven research and ideas

Many of these breakthrough technologies analysed in the cases emerged out of programs that can largely be considered 'blue skies' research. Resources, including people and investment were committed to try and understand a certain field of potential application, such as RCA's focus on

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[4] Giant Magnetoresistance (GMR) was discovered in 1988, by two groups of researchers, one led by Peter Grunberg of Forschungszentrum in Julich Germany, and the other led by Albert Fert of Universite Paris-Sud in France. The two groups were working independently of each other and made the discovery of a fall in electrical resistance when a magnetic field was applied to thin, multilayered metal structures. Grunberg and Fert shared the Nobel Prize for Physics in 2007.

developing the 'TV on the wall'. Liquid crystals was only one of a number of potential display technologies that RCA was investigating for their goal of a 'TV on the wall'; light emitting diodes, electrolumiscence and plasma materials were other display materials also being explored.

When many of the initial ideas and concepts underlying these breakthrough technologies were first suggested they were considered very radical and not, at first, the logical path of the development of the science base. For example when the potential of optical fibres as a communication medium was first mooted by Alec Reeves of STL in the UK in the early 1960s, he suggested that microwave frequencies (which was the technology in pre-commercial development at that time and expected to succeed radio frequencies) be skipped altogether and attention be focused on optical frequencies, even though at the time the gap between the transmission rate of the two was a factor of 100,000 in favour of microwave transmission (Hecht 2004).

Key discoveries that led to breakthroughs in the cumulative history of these technologies were also disproportionately made by young researchers (such as Nick Holonyak from GE who discovered red LEDs in 1962, and Lawrence Curtiss of the University of Michigan, who developed the glass cladding method for optical fibres that achieved low-loss levels). At the time of making their discoveries these researchers had less credibility and reputation within their organisations than more senior and established researchers and had to battle very hard to get the technology taken seriously. This also links in with the role of technology champions, discussed in further detail in a following section. Technology champions were people who did have status, power and reputation within the system and could support these 'radical' ideas.

3.1.4 Threats from the business cycle

Due to the tentative and speculative nature of this blue sky interdisciplinary research and the inability at the early stage to link the programs with ongoing or even medium term revenue streams, these programs were particularly susceptible to movements in the business cycle. The case studies provide many examples of research programs being abandoned just prior to a breakthrough (that was subsequently developed by another organisation) or, more commonly, abandoned in the pre-commercial phase of its development[5], so the basic science is complete but further development work needs to be completed and resources invested to achieve full commercial reality. Of course

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[5] Examples include; RCA withdrawing from the development of LCDs; ICI withdrawing from the development of industrial inkjet printing which was subsequently developed by CCL and spin out firm Domino; Monsanto and Texas Instruments withdrawing from further development of LEDs due to presumed inability to compete with forthcoming Japanese LED development.

these realisations are made only with the passing of time and the benefit of hindsight, but the case studies to provide examples of times when firms have chosen not to cut pre-commercial R&D programs during difficult economic times and have ultimately benefitted in the long run.

The wider macroeconomic environment, particularly commodity prices (oil), and the regulatory environment also were significant drivers of activity in a number of the breakthrough technologies. The most obvious example of commodity prices on breakthrough technology is in the photovoltaics case study and the involvement of oil companies in the development of terrestrial photovoltaic technology. US government regulations on stop-light signals for motor vehicles were also a driver for LED technology and market development. Vehicle safety regulations have also driven the integration of MEMS sensor applications in airbag and anti-lock breaking systems.

3.1.5 The role of technology champions

In each of these research case studies there are a small number of people that were instrumental in moving a technology from the science base into commercialisation. These pioneers as they are often called are able to recognise the value of the technology from very early on, and envisage the ways in which the new breakthrough will (to a limited extent – as there are many quotes from these people about how the progress of a certain technology progressed even beyond their imaginings) change the industrial landscape and create new markets and applications.

These people usually have authority and status within the science system, so therefore can be taken somewhat seriously (as most of the ideas are very left field when they first emerge). The technology champions also have the ability to communicate the value of the breakthrough to non-scientific people – i.e. senior management, marketing departments and government representatives and policy makers. This is especially important in trying to access further resources – people and money, to progress a technology through commercialisation.

3.1.6 Luck

'The harder I practice, the luckier I get.'

Gary Player

The random element of luck can also not be discounted as a factor in breakthrough technology emergence, although the saying, that 'luck favours the prepared' is also apt, because although a researcher may get lucky, in order to fully capture and capitalise on that luck they need to be able to achieve all the other things mentioned above. It is important to mention luck because it emphasises the unknown quantity in scientific development and how we cannot be too formulaic in approaching investing resources in these activities.

3.2 Pre-commercial environment

There are a number of factors which the cases have shown as being important in moving a science discovery out of the lab and into the market. These include focused R&D programs; usually government sponsored but also requiring elements of private investment as well. These R&D programs operate either directly as grants, or as government contracts for R&D services and prototype products. These government programs also usually include the provision of access to specialist testing equipment and the creation of standards, and finally the provision of early, and non-price sensitive customers, such as the military.

3.2.1 Small niche applications for non-price sensitive customers

The case studies highlight a key step for a technology to move from science base to pre-commercial environment are the presence of small niche applications for customers who will tolerate the technology is a less refined and cruder form. This phase is necessary to give the pre-commercial environment focus (otherwise referred to as a mission-driven environment), because up until this point (although there may be some overlap) the process has been about discovery and invention. The mission driven focus of the pre-commercial environment does not end the process of discovery and invention completely, but shifts the focus from exploration to exploitation. This requires different decision making and resources as evidenced in the case study summaries below.

Case summary 1 - Sharp's digital calculators

RCA (Radio Corporation of America) was responsible for many of the early technology advances in the science base in Liquid Crystal Display (LCD) technology. However apart from a small foray into applications in the form of point of sale advertising boards (for which a small pilot manufacturing program was established) and a short-lived joint venture into liquid crystal digital watch displays with Timex Corporation, RCA played no major role in the pre-commercial and commercial development of LCD.

One organisation that proved critical in transitioning LCD technology to the commercial environment was the Japanese firm, Sharp, through their development of LCD digital calculators. This was the first major LCD application to reach the commercial environment after spending some ten years in the pre-commercial environment. Sharp Corporation committed enormous resources to the commercialisation. After initially offering to fund pilot manufacturing of LCD for pocket calculators with RCA, which RCA refused, Sharp Corporation set up their LCD program in 1970. They licensed RCA’s LCD technology for US $3m and assembled a multidisciplinary research team to develop a working prototype of a LCD pocket calculator in 18months instead of the usual product development cycle of Sharp of 3-5 years (Johnstone 1999). The prototype was developed on time and in May 1973; Sharp launched the Elsi-Mate-805 pocket calculator. The product was a commercial success, despite ongoing high power consumption (batteries needed to be quickly replaced), poor image contrast, and problems with the degradation of liquid crystal materials. This was because there was no comparable product on the market that offered the portability of the calculator (all others available where desk based models), and for customers the advantage of portability was more important than the other defects.

Case summary 2 - Photovoltaics and the space race

Non-price sensitive customers were critical in the movement of photovoltaics technology from the science base into the pre-commercial environment. The US space program was the main early customer for photovoltaics and the early revenues achieved from this customer allowed photovoltaics to develop reliability and reputation as a technology despite the extreme high cost of producing energy via the photovoltaic method as opposed to traditional methods of energy generation.

The first satellite was launched in the US in 1957, beginning the space age in earnest. The US military, through the US Signals Corps and the US Air Force Laboratory, began working on and funding research and development into photovoltaics as module power sources. This triggered a period of intense research and development, mainly concentrated on increasing efficiency and robustness of photovoltaic modules (in order to be able to withstand space radiation). The previous drawback to photovoltaics development: prohibitive costs in comparison with other power sources, was no longer an issue in space use since the power unit contributed a minute percentage of the mission cost.

Vanguard I, launched in March 1958 was the first satellite to use a photovoltaic power source. The satellite was launched with two separate transmitters, one battery powered and the other solar powered, using solar cells fabricated by Hoffman Electronics for the US Army Signals Research and Development Laboratory. The battery operated transmitter lasted twenty days. The solar cell powered transmitter lasted until 1964, when it is believed that the transmitter’s circuitry failed rather than the solar cell(Bailey, Raffaelle et al. 2002). The first commercial satellite using photovoltaics, the Telstar, was launched in 1962. Photovoltaics’ proven reliability and longevity meant from this point onwards they became the default power source for space use, and almost all communications and military satellites have been solar powered ever since (Bailey, Raffaelle et al. 2002).

Case summary 3 - Fibre optics and the development of the endoscope

In 1952 Imperial College London, scientist Harold Hopkins received a grant of £1500 from the Royal Society to investigate the use of glass fibre bundles to develop an endoscope. He had recently met a physician who had told of his distress at having to conduct an endoscopy with a rigid glass rod (as was the common practice at the time) (Hecht 2004). Hopkins thought that glass fibres (which at the time were commonly used in illuminated and novelty decorations) may offer some potential. He used the money to hire a doctoral student, and began experimenting with cladded fibre bundles with some promising results. Hopkins sought advice on gaining a patent but because there was some doubt over whether the patent would be granted he did not want to waste the money. He also tried to find an industry partner to develop the endoscope with, but was not successful, describing to Hecht (2004) in an interview that all companies "were dead from the neck up" (p.59).
Hopkins work was published in *Nature* along with similar work being conducted in the Netherlands by Van Heel.

A US medical researcher, Basil Hirschowitz, specialised in gastroenterology saw both *Nature* articles and visited the European researchers. Hirschowitz approached the development of an endoscope from a medical perspective rather than optics (the background of the previous researchers). In attempting to replicate both Hopkins and Van Heel's work, Hirschowitz found the glass did not carry light in the way the article suggested. He and his research student, Lawrence Curtiss, started from scratch developing a new glass recipe and technique for making and cladding the glass fibres. Through trial and error, Curtiss developed high index glass fibres clad in low index glass, achieving the best light transmission to date (Dec 1956). Constructing and testing an endoscope was swiftly completed, two months later they had developed a prototype endoscope and trialled it on a patient. The following year the technology was licensed to American Cystoscope makers on the condition that Curtiss helped them start production. Curtiss took a semester off university to work on the production, but never went back. Commercial trials started in 1960 and sales soon after. The device was a success from the start – the company expected to sell 2000 instruments over the 17-year life of the patent, but they sold 2000 in the first year.

3.2.2 Complementary developments

The path of a breakthrough technology is not solely dependent on the success or failure of the technology alone, but also the success of other complementary and competing technologies that are also being developed. LCD was not the only flat panel display technology under development in the later part of the twentieth century. Other display technologies included plasma and light emitting diodes (LEDs). The plasma flat panel display TV were the first to be commercially successful, only to be quickly followed by LCD displays (which had advantages in materials survival and cost reductions through economies of scale), which are now in turn facing competition from LED (organic or OLED) flat screen displays (although OLEDs have advantages in reduced power consumption and brighter contrast they have not achieve costs reductions through economies of scale yet).

The case studies highlighted multiple examples of where the case study technology found a pathway forward into the pre-commercial and commercial environment through the advance of another technology. The most obvious example is lasers and the use of fibre optics as a communication medium.

Case summary 4 - The laser and fibre optics

The development of fibre optics was at that time (1960s) focused on developing low loss fibres for optical transmission, but researchers involved in the low loss fibre research knew that without a stable, long lifetime optical signal source, optical communications would not be possible. The semiconductor laser diode was developed by four independent groups of scientists simultaneously in September-October 1962, with a research team at GE labs credited as the first. However, as is the case with many materials based technologies it would be May 1970 until a prototype continuous laser that could operate at room temperature was developed. This prototype came one month before the announcement of low loss fibres developed by Corning Glass Works. These two advances allowed fibre optic researchers to start to put together the transmission channel (fibres) and a light signal (semiconductor lasers) of optical communications for the first time.

Neither was a finished product, the lasers would only last a few hours at most and the fibres were brittle and prone to break with temperature changes. Even though the potential of optical communications had been reinforced there was still much research and engineering to be completed (Hecht 2004). Bell Labs kept developing lasers, and by 1977 had lasers with a lifetime of a million hours, which were viable for telecommunications. In this same period optical fibres progressed through three generations of fibres; single mode low loss fibres, multimode graded index fibres, before finally returning to single mode fibres with the ultimate low loss fibre. The target market of optical communications; the telecommunications industry, demanded a very high level of reliability and longevity before optical fibres could be seriously considered. The complementary progress of both of these technologies led to the first optical fibre system trials in the late 1970s and early 1980s.

Case summary 5 - Fibre optics and the discontinuation of millimetre waveguides

The development of fibre optics also provides us with another example of how technologies develop in an environment of other competitive and complementary emerging technologies. Some industries, namely telecommunications, aerospace and the military, move in very long innovation and product development cycles. Technology foresight needs to work some decades in advance, and communications using frequencies in waves (microwaves) and millimetre waveguides[6] were considered the next logical technological step for telecommunications in the 1950s. US based AT&T invested extensively in the development of millimetre waveguides. In the UK, the British Post Office (who had responsibility for telecommunications provisions) had more than 100 researchers on their millimetre waveguide research projects (Hecht 2004).

Despite their popularity millimetre waveguides had serious limitations. Signals would degrade if the waves had to go around corners, therefore all the waveguides had to be installed in completely straight lines, a difficult task and expensive task in urbanised areas. This limitation was a major concern for UK researchers, as noted in the following quote “…Millimetre waveguides were as ill-matched to winding along the tangled streets of London as rigid metal pipes were to looking down patient’s throats. Post Office engineers wanted a cable they could snake through utility ducts already buried underground” (Hecht 2004, p.118). However, Bell Labs would not be dissuaded from millimetre waveguides, the lower density of the US population and the telecommunications monopoly led them to believe that the challenges of millimetre waveguides could be overcome, “…No one (at Bell) pretended it (millimetre waveguides) were going to be cheap or easy, but with government regulations assuring a return on their investment, AT&T was ready to spend untold billions” (Hecht 2004, p161).

The reluctance of the telecommunications industry (AT&T in particular) to move away from millimetre waveguides despite their growing list of inadequacies slowed the pace of the development of fibres optics as a communication medium. However, in other ways this helped the development of fibre optics, as millimetre waveguides provided the standard to which fibre optics need to match and exceed, it also meant that a range of firms not associated with telecommunications would feature in the ultimate winners of the commercialisation process, including glass maker, Corning and the small telecommunications carriers MCI and Sprint in the US.

3.3 Corporate strategy towards commercial environment

This section provides some analysis of the strategic decision making of organisations involved in transitioning breakthrough technology from the pre-commercial environment into the commercial environment. Activities discussed will necessarily span both the commercial and pre-commercial environment but primarily involve commercial actors in the form of firms.

Corporate strategy is a key factor in understanding the direction that such science based technology commercialisation takes. In the absence of a known market and applications with functions and

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[6] Waveguides are long tubes either made of electrically conductive material of non-conductive insulation. Millimetre waveguides were named as such because the wavelengths guided were a number of millimetres (2-5mm). Waveguides provide the boundaries for these waves, directing them to their destination.

advantages not necessarily known or appreciated by customers, organisations must have other strategic reasons for pursuing technology development other than market demand.

This section examines four areas of corporate strategy in further detail. Strategy in regards to market position (including strategy to potentially cannibalise a firm's existing market with new technology), strategy in regards to accessing new technology (internally and externally), strategy in terms of the vehicle of commercialisation used (start-up, spin-out or corporate unit) and finally strategy in terms of funding technology development (government grants, R&D contracts, alternative revenue streams etc).

3.3.1 Market position

Breakthrough technology commercialises into an environment with little, if any, market feedback. The decision to enter a market with a new application based on breakthrough technology is based on reasons aside from current market demand. These reasons include the belief of the firm, or key individuals within the firm, that a new application will result in a significant market opportunity. These individuals (more than product champions, but similar to technology champions) include people like 'Dr Rocket' at Sharp[7].

Other reasons include strategic supply and diversification. Monsanto became involved in the development of light emitting diodes because of their access to phosphorous. Oil companies became involved in the development of photovoltaics through mergers and acquisition activity during the oil crisis of the 1970s and as a result of having profits available for investment and a concern in maintaining energy supply and security.

3.3.2 Knowledge sourcing

Another area of corporate strategy is the decision making involved to either bring in new knowledge or to develop in-house capability in regards to a technology. In all of the cases studies two types of broad technological capability were visible; capability around discovery and capability around

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[7] Dr Rocket was the nickname given to Sasaki Tadashi by colleagues at Sharp. A pocket calculator had been produced by Texas Instruments in 1967 but in developing a marketing strategy for the calculator Texas Instruments had focused on the specialised office market. Tadashi realised that this vastly underestimated the market for such an application. His aim was to create a calculator that was "small enough to carry around on you…and one that could be readily used, not by a clerk, but by a greengrocer, or even a housewife" (Johnstone 1999, p42). Tadashi's goal was met with disbelief in the industry and his own firm but would ultimately prove inspired, as the market success of the Sharp LCD pocket calculators and pocket calculators generally, would later show.

developing and manufacturing applications. Many firms, particularly in the US in the 1960s period had capability in a number of fields of discovery, however in capability of developing applications and manufacturing applications there were fewer.

In the LCD case, Sharp acquired technology licenses for the dynamic scattering mode LCD from RCA and then invested heavily (US$200m+) to develop a manufacturing capability in LCD. RCA had many resources to draw on for the scientific development yet could not afford or justify the full manufacturing of displays. This was primarily because they did not want to cannibalise their existing and highly profitable CRT market. Consequently, RCA refused to take a long term and product position in the LCD market despite doing a lot of the original research.

Corning provides another example of knowledge sourcing strategy. Corning decided to extend their knowledge of manufacturing to create capability in discovery as well. At the time of the early days of fibre optics development, Corning was a medium sized glass manufacturer in upstate NY. They did not have the resources to compete in R&D against Bell Labs in the telecommunications market yet they saw optical fibres as a way to expand capacity and possibly exploit their know-how in the use of speciality fused silica[8].

To support the R&D program Corning contacted a group of cable manufacturers; their logic was that target customers were current telecommunications cable providers, if optical fibres were to emerge as the next generation fibre, they would still need to be produced as cables. A group of five international cable manufacturers including Pirelli in Italy, Siemens in Germany and BICC in the UK agreed to support the program via the payment of an annual fee. This payment did not entitle any of the cable manufacturers to any IP relating to the R&D project, but entitled them to be kept up to date with progress and have first rights to license and buy any resulting cables. Corning's decision to expand their technical capability in glass manufacturing by supporting it with a base in basic optical fibre research allowed Corning to develop and ultimately profit from the optical fibre revolution.

The Inkjet printing case study provides a further example of knowledge sourcing strategy, but in this case in the opposite direction. CCL had completed much of the basic research around developing a new method of industrial inkjet printing under a contract for the chemicals firm ICI. ICI decided not to pursue the research and allowed CCL to retain the intellectual rights to the work they had

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[8] Silica was more difficult to work with than traditional glass. Traditional glass melts and can be pulled into fibres at between 1200-1500 degrees, silica needs temperatures well over 2000 degrees to even soften. Silica also has the lowest refractive index of any glass (Bell 1988).

contracted them to do. CCL developed this research over a number of years before creating a spin-out company to fully resource and develop a manufacturing capability for the technology. The resulting spin-out company was named Domino.

The previous three examples have highlighted three methods of how knowledge sourcing happens in this pre-commercial environment

1. Bringing in new knowledge then investing to create internal capability in both discovery and development.
2. Building on existing commercial and manufacturing capability drawing in resources to develop a discovery capability that can drive a future direction of development.
3. Building on an existing capability for discovery and adding resources – in this case through a spin-out company, to develop the technology.

3.3.3 Commercialisation vehicle

Another area of strategy in the pre-commercial area of development relates to the commercialisation vehicle – by this we mean the vehicle in which the technology is incubated in the pre-commercial stage. Examples include start-up, spin-outs and corporate units. We have already seen examples of spin outs (Domino from CCL) and corporate units (Sharp and Corning). In the case study technologies the majority of pre-commercial development is incubated in a corporate and then to a lesser extent spin-out vehicles. This is no doubt a factor of the development stage of the technology – as the technology develops and uncertainty surrounding it decreases, we see more spin-out and then start-up activity.

Start-up activity appears to be much less than expected of radical industrial development. This is probably a result of the technologies selected, and their concentration in physics based sciences with high barriers of entry (due to equipment and materials needed) than in other technology sectors. There are only a few examples of start-up activity in the early days of a technology. Start-up activity increases as technological uncertainty decreases. E.g. LCD – handful of start-ups founded by early pioneers of the technology, had limited success and lasted only a few years. One example of a start-up in the early days of a technology is NVE Corp, which has a specific application development strategy that supports R&D activity in main area of pre-commercial interest, MRAM.

Case summary 6 - Non-volatile Electronics (NVE) Corp

NVE was founded by former IBM and Honeywell researcher James Daughton in 1989. The company was founded one year after the initial GMR discovery with the aim of exploiting the GMR effect to create smaller and more sensitive magnetic sensors for a broad range of applications and then later developed the long term goal of developing magnetic random access memory (MRAM)[9]. Magnetic sensors have many applications across a number of industries including landmine sensors, sensors in pacemakers and other medical equipment, anti-lock breaking systems and engine controls in automobiles.

When Daughton left Honeywell to start NVE he licensed some Honeywell technology relating to magnetoresistance and MRAM. However the struggle to develop such pre-commercial technology proved very difficult for the small technology company (60 employees). By 1994 NVE had received over $5.5m in US government research contracts through both the SBIR (Small Business Innovative Research[10]), ATP (Advanced Technology Program[11]), Defense Advanced Research Projects Agency (DARPA))[12] and the US Navy as well as $2.5m from Norwest venture capital partners. Their first research contract was through the ATP and was $1.7m over three years to develop a one-megabit chip(Carey 1994) and others followed relating to the development of MRAM (from the National Science Foundation (NSF)) and biosensors (also NSF). Although this research did not yield any immediate MRAM products[13], NVE continued to receive government funding

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[9] MRAM is a new form of electronic memory made using nanotechnology and using electron spin to encode data. MRAM has been called the 'holy grail' or 'universal memory' because it has the potential to combine the speed of static RAM, the density of dynamic RAM and the non-volatility of flash memory (Businesswire 2004).

[10] The Small Business Innovation Research (SBIR) programme offers contracts with a US federal government agency for the development of technology. The contract provides 100 per cent of the costs involved in the project and is part of the government procurement process. This contracting activity provides an important source of external finance for US NTBFs with the programme annually awarding approximately 4,000 contracts with total funding in the order of US $2 billion (£2.7 billion) (Connell 2006).

[11] ATP was launched in 1998 under the Clinton administration with an annual budget of approx $430 m (US). The program was administered through the Department of Commerce National Institute of Standards and Technology and was aimed at supporting industrial research in enabling technologies. The ATP was a public-private partnership with the program making competitive awards of funding on a cost-share basis to individual companies and larger awards to joint ventures (Wessner 2001). The program was suspended under the Bush administration in 2005 and disbanded in August 2007.

[12] Particularly the DARPA GMR consortium program ($5m in 1995) and the later SPINTRONICS program (2000-2006) worth $100m over the six years and in which four companies; Honeywell, Motorola, IBM and NVE participated in. The project was aimed at developing MRAM applications for satellite memory but more widespread industrial applications were also envisaged (McCray 2009). In addition to these two engineering focused programs DARPA also ran a $30m basic research program called SPINS. Started in Jan 2000, the aim of the program was to encourage a spintronics community between scientists (both university and industry based) and government R&D labs. The program funded an annual conference and various workshops as well as grant funding for basic research into spintronics (McCray 2009).

[13] In 2003 Cypress Semiconductors announced a prototype MRAM 128 kb chip in a partnership with NVE (Cypress Semiconductors invested $6m in NVE in 2002 for a 24% equity stake)(Businesswire 2002). In 2005 Cypress announced another batch of MRAM samples 256kb chips but as of yet there is still not product on the market. Freescale (Motorola's MRAM spin out) made available the first commercial MRAM product in 2006.

throughout the 1990s and 2000s. Whilst the development of MRAM was the focus of the majority of government contracts during this time, NVE leveraged its expertise in GMR materials to develop GMR sensors and isolators which they manufactured and sold to customers[14] as an ongoing revenue source to support firm development and continued exploitation of their R&D program. NVE's products and services included magnetic field sensors[15], gradiometers, arrays, and assemblies; magnetic-based isolators; MRAM research and development in; magnetic modeling/simulation; custom design services; back-end IC processing; and custom thin-film sputtering (NVE 2009).

Work on MRAM continues at NVE although the firm could now be described as a contract R&D supplier. NVE is one of the smallest firm operating in the MRAM space; competitors include Motorola, IBM, Micron, Honeywell and Cypress Semiconductors. All of NVE's revenue comes from either R&D contracts or the sale of sensors and isolators mentioned above, both of these markets have potential for multi-million dollar growth. For the 2009 financial year, total revenue increased 14% to $23.4 million from $20.5 million in 2008. The increase was due to a 7% increase in product sales and an 81% increase in contract research and development revenue. Net income for fiscal 2009 increased 36% to $9.78 million (NVE 2009). No revenue currently comes from IP license fees, despite NVE's strong IP position in regards to MRAM[16]. In the past, they have licensed out their MRAM IP to Motorola (since 2002), Honeywell (since early 1990s), Agilent (since 2001) and Cypress Semiconductors (since 2002); but currently Motorola pays no fees on their licenses and Cypress Semiconductors has since ended their agreement.

The future direction and application of MRAM is unknown. The market potential of such technology is well recognized but the path to achieving a commercially viable product is not. MRAM could progress in such a way that NVE's patents become vital to all the large corporates integrating MRAM into their products, in which case NVE could profit massively from their early participation in MRAM. On the other hand, a key breakthrough could emerge from elsewhere[17] and make the NVE IP portfolio less valuable. The NVE case shows that small firms can participate in breakthrough technology, but from a position where the majority of their breakthrough R&D programs are externally funded (either through government or client R&D contracts) and/or a profitable product revenue stream in related products is also available to support technology development.

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[14] Customers include St Jude Medical purchasing spintronics components and Agilent Technologies.

[15] The largest market for NVE sensors is in industrial robots and implanted medical devices (such as pacemakers) and weapons sensors (Nanotechwire.com, 2006).

[16] The firm has over 50 US and 100 International patents the majority relating to MRAM. The patents are also described as expansive (Jutiagroup.com 2009).

[17] An advance by MIT researchers called 'MRAM tunneling' in 2006 is such an example.

Case summary 7 - Start-up firm case study in the Photovoltaics industry – Pacific Solar

Pacific Solar was an Australian based photovoltaic start-up company that traced its origin back to University of New South Wales (UNSW) in Sydney, Australia. Pacific Solar founder, Dr Martin Green, was a researcher at UNSW, and became interested in photovoltaics when Telecom Australia began equipping its microwave repeaters in remote areas with photovoltaic cells as power source. In the 1980s, Green led a team in UNSW focusing on improving the efficiency of crystalline silicon cells (Perlin 2002). The fundamental research was funded by the Australian Research Council (ARC) and further development by National Energy Research, Development & Demonstration Council (NERDDC) and New South Wales State Energy R&D Fund (NSW SERDF). In 1985, using proprietary 'buried contact' technology, Green's group produced the world's most efficient photovoltaic cell at 20%. UNSW immediately considered commercializing this technology and was in licensing negotiation with Tideland Energy, an Australian photovoltaic company founded by Stuart Wenham and Bruce Godfrey, (who had both studied under Green) (Watt 2003). In the same year, BP bought Tideland Energy to establish BP Solar Australia and acquired a 20-year exclusive right to the Buried Contact technology (Green 2007).

From 1989 to 1995, Green's group researched and invented Crystalline Silicon on Glass (CSG) technology. And in 1995, Green and Wenham approached Pacific Power, a utility company in Sydney, in an attempt to gain investment for commercialisation. Pacific Power was very interested but wanted full exclusivity. Ultimately, Pacific Solar was set up. Pacific Power invested $50m for 70% equity, Unisearch Limited, UNSW's commercial arm, took 30% share and all patents were transferred to Pacific Solar (1998).

From 1995 to 2000, Pacific Solar focused most of its efforts in a 5-year development program to bring the CSG technology to a manufacturing- and market-ready state. In 1996, it also began to pursue a more near-term opportunity by obtaining funding of $5.9m over a period of three years from R&D Syndicate (a consortium consists of industry players and government agencies) to develop an inverter, which is a device linking photovoltaic modules to electricity grid and promised to ease the installation process of photovoltaic systems for households (Pacific Solar 1999, 2000, 2001, 2002).

Over the next few years, Pacific Solar made steady advances in its CSG technology and integrated its inverter into an easy-mount rooftop photovoltaic system called Plug&Power. In 2000, it began selling the Plug&Power system incorporating its own inverter and mounting structure and outsourced photovoltaic modules. Its research in CSG technology, however, was still ongoing and in its annual report in 2000, it expected to have CSG cells in mass production by 2004 (Pacific Solar 2000).

To facilitate a move from a research oriented organization to one focused on commercial operations, Pacific Solar actively promoted its Plug&Power system. In 2000, to increase sales and obtain extra funding, it teamed up with Eurosolare, the solar subsidiary of Italian oil company ENI, which became Pacific Solar's distributor for Plug&Power in Europe and invested in Pacific Solar for 25.6% equity. Pacific Solar also obtained a $500,000 grant from the federal government under the Renewable Energy Commercialisation Program (RECP) to further develop the Plug&Power system (Pacific Solar 2001). Sales in Plug&Power system grew quickly, achieving annual revenue of $1m in 2002. Pacific Power also won $1m in grants under RECP to take its CSG technology into a manufacturing-ready state during the following year (Pacific Power 2008).

In late 2002, Pacific Solar's major investor and source of funding, Pacific Power, became an entity wholly owned by the NSW state government[18]. In December, NSW government pledged a further $6.5m for Pacific Solar to take CSG forward (ABC 2004). However, in early 2003, unexpected changes to government funding support programs caused Pacific Solar to abandon its CSG ambition (Fyfe 2003). Details on which funding changed could not be found. But speculation suggests that the $6.5m pledge of the previous year was scrapped as the then federal government moved from funding renewable energy to investment in clean coal technology in 2003 and the NSW state policy changed with the federal policy. In June 2004, Pacific Solar sold its physical assets and worldwide rights relating to the CSG technology to a new German company, CSG Solar AG, which was formed with financial backing from a consortium of European investors. CSG Solar AG formed an Australian subsidiary, CSG Solar Pty Limited, which continues to operate the pilot-line facility built in Sydney.

3.3.4 Funding

The final area of corporate strategy analyzed across all of the case studies relates to financing of the pre-commercial stage. In this report there have already been cited numerous examples of how organizations supported the development of pre-commercial technology, including accessing government R&D programs and R&D contracts, funding new areas of technology development through existing revenue, and gathering external funding support from customers (such as in the example of Corning and the group of cable providers that supported Corning's initial optical fibre research program). In this section details of these funding support mechanisms and their effects on technology development are discussed.

Government R&D contracts

Government R&D contracts were an important source of pre-commercial technology development in all of the cases analyzed. In the LCD case R&D contracts were for military applications in display devices (mainly for aircraft cockpit displays). In fibre optics development government contracts were frequent as a result of the telecommunications function still being under government control and/or government monopolies in most countries. There was however other R&D contracts for the

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[18] http://web.archive.org.web/20030413132015/pacificsolar.com.au/html/MediaReleases.html

development of solutions for military use (such as ship communication systems). Photovoltaics early development was largely funded by the space program in the US and the need for remote power applications in other countries (remote telecommunications in Australia, and coastal lighthouses in Japan). In the more recent case of GMR development government (US military) contracts supported the development of magnetic sensors for land mine detectors. In each of the government contracts the activities supported are pre-commercial technology development generally, and for development of specific niche, high cost, low volume applications primarily for military use. The use of these contracts varies greatly between countries. The US has the most prevalent activity in these types of contracts.

Government R&D and other programs

Many other governments support technology through specific R&D programs which are aimed at pre-commercial support in technology and market development around a group of applications. These programs provide not only R&D support and subsidies for specific areas of breakthrough technology development, they also provide access to specialized equipment, forums for the establishment of standards, and in some cases direct financial support for establishing new industries. Public procurement also provides another mechanism for government to support breakthrough technology in the pre-commercial environment. The cases highlight examples of governments procuring R&D but also, and in many cases more critically acting as deep-pocketed first customers and procuring first quantities of technologies. Government customers include military, health and energy departments. The below case study summaries provide an overview of different areas national policy action.

Case summary 8 – Comparative policy action in photovoltaics support

United States of America

The oil embargo in 1973 triggered a period of intense growth of photovoltaics. In 1970 US domestic production of oil peaked and in 1974 the US received their first 'oil shock' from the oil embargo (Hart 1983). The Government realized the importance of energy security and implemented policies, such as public procurement and tax credits, to encourage the adoption of renewable energy. In 1973 the US Solar Energy Research Institute[19] at Golden Colorado was established and in 1974 the Solar Energy Research, Development and Demonstration Act was passed through Congress. This provided $75m (US) of funding for appraising the potential of a number of alternative energy sources including photovoltaics. This was followed by the 1976

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[19] The US Solar Energy Research Institute was the designated national laboratory of the U.S. Department of Energy (DOE). It changed its name in 1991 to the National Renewal Energy Laboratory.

Energy Conservation and Production Act, which set up a stream of funding for a commercialisation plan for photovoltaics. In addition to this commercialisation plan, two years later, in 1978, the Federal Photovoltaics Utilization Program (FPUP) was also established. FPUP's aim was to encourage photovoltaics commercialisation by providing an initial market through government procurement, on which it was hoped a private uptake of PV cells would follow (Hart 1983).

The FPUP made available varying amounts of funding for government departments to use in the purchase of PV equipment for federal facilities. The first program, made available $12m, the second $98m over three years (1979-1981), and the third $1.5billion over ten years[20]. This third program provided funding to various 'block purchases' aimed at creating different markets; blocks one and two were aimed at purchasing PV devices suited to small and remote applications; blocks three and four for intermediate remote applications; and block five was aimed at residential applications (Hart 1983). The US government was clearly the most active in encouraging the development of the PV market in the 1970s and early 1980s. Opinions on the success of the US programs in accelerating the commercialisation of PV applications are mixed (Hart 1983; Sklar 1990). On the one hand sales of PV equipment increased dramatic in the years of the programs' operations (Sklar 1990), but, on the other hand, the lack of connections between individual procurement purchases and energy cost reduction advantages and overall market penetration meant that the US did not see lasting industry-stimulating benefits of the government procurement programs (Hart 1983).

Australia

In the 1970s, the Australian government generously funded Telecom Australia, a quasi-public agency, to provide every citizen, no matter how remotely situated, with telephone and television service comparable to that enjoyed in the larger population centres. Due to the size of the country and the sparseness of the population, a real problem was reliable power supply. Photovoltaic panels had significant advantages over other power sources in terms of maintenance, reliability and longevity. This led to significant deployment of photovoltaic panels by Telecom Australia, and essentially started the photovoltaic industry in Australia (Perlin 2002).

Australian government policy was initially focused on support R&D programs, particularly at the University of NSW. Photovoltaic research started at the University of NSW in 1981 as the Microelectronics Special Research Centre, later evolving into Photovoltaics Special Research Centre and currently the Special Research Centre for Third Generation Photovoltaics. In total the various research centres have received $24m in core funding plus external grants. From 1985-1995 the Australian Federal government provided $25m in PV related funding (to both universities and industry) in the form of tax concessions, R&D credits and grants (Watt 2003). In 1989 the Australian Government funded the Centre for Photovoltaic Devices and Systems at UNSW (Perlin 2002) with a

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[20] Despite the provision of $98m in the second program only $25m was actually expended. The third program ($1.5billion over ten years) also suffered from budget cuts after the 1981 change of administration (from President Carter to President Reagan).

multimillion dollar investment. This was matched by the NSW State Government. In more recent time, financial government support for the PV industry has declined as funding is also directed towards 'clean coal' technology.

Germany

Government support in Germany for the PV industry comes from both the national and regional, or *lander* level. An example of such a regional program is the state of Saxony-Anhalt, a federal state located in the east of Germany, and widely cited as the Solar Valley. It has the highest density of PV supply chain worldwide and accounts for half of all solar cells produced in Germany in 2008. Many solar companies have been attracted to locate in Saxony-Anhalt by a number of factors: Saxony-Anhalt gives generous investment incentives to cover up to 50% of capital expenditure; the state investment corporation, IBG, actively provides equity funding; the close proximity of equipment suppliers, manufacturing setup and project realisation is faster; and the state has several research institutions, e.g. the Fraunhofer Centre for Silicon Photovoltaic (Welles 1998).

An example of policy at the national level includes the 1991 'Feed in' tariff system. Feed-in tariff is an incentive structure set by government legislation, where the national or regional utilities are obliged to buy the electricity generated by renewable sources at above-market prices. Germany's feed-in tariff was introduced in 1991, but became significantly influential only when it was modified in 2000 under the Renewable Energy Sources Act where the feed-in tariff was raised above the retail electricity prices and guaranteed for up to 20 years. The feed-in tariff for photovoltaics is particular substantial, being the highest of all renewable sources and almost 10 times higher than the market price of electricity. Such a strong incentive brought an unprecedented expansion of the German market, where the capacity of photovoltaics installed increased by 40 times, from 62MW in 2000 to 2405MW in 2006, making it the largest market for photovoltaics. For many leading photovoltaics firms, the German market has been the primary source of revenue in the past nine years, although Spain has become more important since the introduction of feed-in tariffs there in 2007.

Case summary 9 – Catch-up policies for Taiwan and South Korea in the LCD market

The 1990s marked the start of movement of LCD applications into large area displays, the third wave of LCD technology applications (the previous waves of applications being small area LCDs; calculators and digital watches, and active matrix displays; laptops and televisions). Japan dominated the early large format display industry, accounting for 95% of the market (Asakawa 2007). By 2007 Japan had 15% of the market and new-comer nations South Korea and Taiwan accounting for 40% of the market each.

Large format TFT-LCD manufacturing is challenging and capital intensive, a fabrication plant for generation 3 TFT-LCDs required US$500m in start-up investment (Generation three circa 1996-1998) (Linden, Hart et al. 1998). The TFT-LCD market also evolved rapidly, mainly with the increasing size of the displays. The capital intensive nature of production made set-up timelines long, and firms could quickly lose competitive advantage if their investment plans and industrial evolution were out of step. This also creates what Mathews (2005) refers to as the crystal cycle – periods of under supply of a new generation product, followed by rapid expansions and then oversupply and industrial downturn as profit margins are squeezed. South Korea and then Taiwan made successful entries into the TFT-LCD markets during periods of both overall economic downturn (South Korea, 1992 recession and Taiwan 1998 Asian Financial crisis) and industrial downturn. Mathews (2005) notes further that no firm was able to successfully enter the TFT-LCD market at a time of economic growth (Mathews 2005). Both South Korea and Taiwan also benefited from government assistance in competing in the TFT-LCD market.

South Korea

The top three firms in the Korean display industry; Samsung, Hyundai and LG acting independently of government, entered the TFT-LCD market IN 1994-1995 by establishing production facilities with purchased equipment and advice from Japan[21]. Each of the three firms had invested in excess US$800m each by the late 1990s and had gained market share from Japan by 1995-1997 (Linden, Hart et al. 1998).

Government support early on was minimal, confined to land subsidies in business parks and joint research programs through the Ministry of Trade, Industry and Energy (MoTIE) (e.g. 1994 US$6.4m program for notebook PC displays). By 1995 the government was concerned about an over-reliance on Japanese production tools the Korean government established EDIRAK (Electronic Display Industry Research Association of Korea) a public-private consortium with a planned five-year research expenditure of US$220m .

Taiwan

The Asian Financial crisis and resultant industrial downturn in TFT-LCD between 3rd and 4th Generation fabrication (1997-1998) allowed Taiwanese firms to enter the market. There had been previous attempts by Taiwanese firms (particularly Acer) to enter the market, but barriers to entry were too high. This coincided with efforts by the government-owned Industrial Technology Research Institute (ITRI) to build industrial capability in TFT-LCD to complement Taiwan's' increasing strength in semiconductors (Mathews 2005). A government program of 1992 identified TFT-LCD's in a list of 69 currently imported components that could be made in Taiwan. The program offered tax incentives, (critically) subsidized loans and research grants to private firms willing to commence local production in any of these 69 identified components. Also ITRI's microelectronics research lab is given funding (US$92m in 1993 for a four-year program) to hire top engineers and set up pilot manufacturing which later become full-scale manufacturing facilities. In Taiwanese case a critical aspect of government support was access to finance to establish fabrication plants. This support has been identified as being more critical than support for knowledge transfer (Hu 2008).

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[21] Samsung actually opened a R&D lab in Japan in 1993-1994 during the first TFT-CD oversupply downturn. The lab was able to recruit unemployed Japanese engineers and transfer their know-how into the construction of their 2nd generation fabrication plants (Mathews 2005).

The industrial downturn and financial crisis meant that Japanese firms were interested in licensing their technology to the Taiwanese, both for revenue and as a way to slow the Korean expansion. Five new Taiwanese firms entered the market; Acer Display Technology, Unipac, ChungHwa Picture Tubes, HannStarr Display and ChiMei Optoelectronics and were followed two years later by Quanta Display, Innolux and Toppoly (Mathews 2005). The majority of Taiwanese output was exported to firms such as Dell and Compaq (Linden, Hart et al. 1998).

Corporate funding

Corporate funding from internal revenues is the other significant funding source for pre-commercial breakthrough technology support. With the acknowledgement that much of the breakthrough technology analyzed in these case studies emerged from corporates, also comes the acknowledgement that by and large these breakthrough technologies emerged from large firms as opposed to small ones. This may suggest that in the case of science-based technologies successful commercialisation favors larger firms, or has done so in the past.

Other funding mechanisms

In a number of the case studies, novel funding mechanisms, what we have described as 'money clubs' existed to support pre-commercial breakthrough technology development. Corning used funding from a group of international cable providers (their potential customers for any new form of optical fibres) to support their earlier research on single mode optical fibres. Elmjet, one of the later spin out firms from Cambridge Consultants, developing binary deflection continuous inkjet technology created a User Council. Potential customers were invited to join this user council with an annual membership fee of £50,000. Six firms were invited to join the user council and they were from different market segments and not in direct competition with each other. For their membership these six companies had access to information on how the technology was developing and priority ordering for any emergent product.

Absence of Venture Capital

The technologies investigated in the case studies highlighted few examples of the use of venture capital funding to support technology and market development. This should not be a surprising result given the breakthrough nature of the technologies examined. Venture capital is a source of funding for a limited number of firms with very specific characteristics in terms of technology development and market opportunity. Firms that seek equity investments are typically small firms rich in intangible assets such as technology and specialist knowledge but lacking in other forms of assets that provide the means to access other forms of external finance such as debt finance. Venture capital funds are typically looking to invest in firms that have a great opportunity for extra-ordinary profits and the ability to make a return on investment (equity share returned back to the fund in form of cash) within ten years. As a result venture capital funds would look to invest only in technology applications that were in the commercial environment.

In examining the long periods of time these breakthrough technologies spend in the pre-commercial environment the limited activity of venture capital in these breakthrough technologies is not surprising. This is not to say that venture capital is unimportant in commercializing technology. If the cases examined further the successive waves of innovation and application development of these breakthrough technologies when they are established in the commercial environment, venture capital financing would feature regularly. Issues with the availability of venture capital in this environment for new technology based firms are well known[22] as to activities by governments aimed at increasing the supply of venture capital finance (OECD 2006). Government activities aimed at increasing the supply of venture capital finance to new technology based firms can only play a specific and limited role in the commercialisation of science-based breakthrough technology. This is because venture financing is a suitable means of funding technology development for a specific set of firms operating at the end of the overall commercialisation cycle that we have examined in these cases.

4. Conclusions and implications

This research set out to address three questions.

1. How do commercialisation patterns emerge for breakthrough technologies?
2. What are the key factors/ inflection points in these commercialisation patterns for breakthrough technologies - both successful and unsuccessful commercialisations?
3. How does the UK perform in the commercialisation of breakthrough technologies?

This section summarises the case study evidence and analysis in answering these questions.

4.1 How do commercialisation patterns emerge for breakthrough technologies?

The commercialisation patterns of breakthrough technologies are best illustrated by what Adner and Levinthal (2002) refer to as speciation events. In that progress is cumulative and slow up to a certain

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[22] Please see Sharpe, Cosh et al (2009b) and the CIKC/ NESTA crossover report for this project Sharpe, Cosh et al (2009a) for further details on these issues.

point of discovery or breakthrough, and then dramatic and quick evolutionary change takes place and new technology with new potential applications, markets and industrial direction, emerges.

The evolutionary approach highlights three further characteristics of breakthrough technology commercialisation; the process involves long time lines; successful breakthrough technologies are comparatively rare events; and breakthrough technologies have the ability to cause dramatic changes in the industrial landscape.

This report has illustrated three phases of commercialisation; the science base, the pre-commercial environment and the commercial environment. In each of these phases certain activities and characteristics dominate; in the science base, activities of discovery; in the pre-commercial environment activities of establishing potential and reputation of technology; and finally the commercial environment is dominated with executing on this established potential. Although these activities are associated with different phases, they do not exclusively exist only in these respective phases, discovery activities continue in all phases for example.

Studying the activities dominating the different phases allows us to differentiate the phases and give adequate explanation and analysis to the actors and the decisions they make in context. Citing people at the centre of the analysis also emphasises the importance of people; these are case studies are about people, their interactions, movements, decisions and achievements.

4.2 What are the key factors in these commercialisation patterns?

Throughout this report we have identified two transition periods in the commercialisation of science-based technology; the transition from science-base to pre-commercial environment, and the transition from pre-commercial to commercial environment.

A number of factors in each transition have been identified and are summarised in figure 5. Factors that drive technology from the science base to the pre-commercial environment include interdisciplinary interaction, time, a background of blue skies research activity that is sheltered from the business cycle, technology champions that spread the word of the potential applications and establish direction for the new technology, and finally, luck. Luck that the right people will meet at the right time and that certain research will be supported at the right time.

Factors that see a breakthrough technology transfer from the pre-commercial environment into the commercial environment include the development of niche applications and/ and for non-price sensitive customers. These early applications build the reputation of the new technology.

Another key factor is corporate strategy in regards to a new technology and the resources that firms (primarily large firms) invest in the development of this technology. Strategic areas include;

- Whether or not to pursue a market and product position with a new technology,
- Whether to extend their field of knowledge in regard to a new technology and how this is achieved (developing internal knowledge capacity or bringing in external knowledge in the form of technology licensing)
- Whether to cannibalise existing products/ markets with new technology
- Vehicle of commercialisation – start-up, spin out or corporate unit
- How to support pre-commercial development; through pursuit of R&D contracts, participation in R&D programs (usually cooperative), internal revenue or external sources such as 'money clubs' and risk capital.

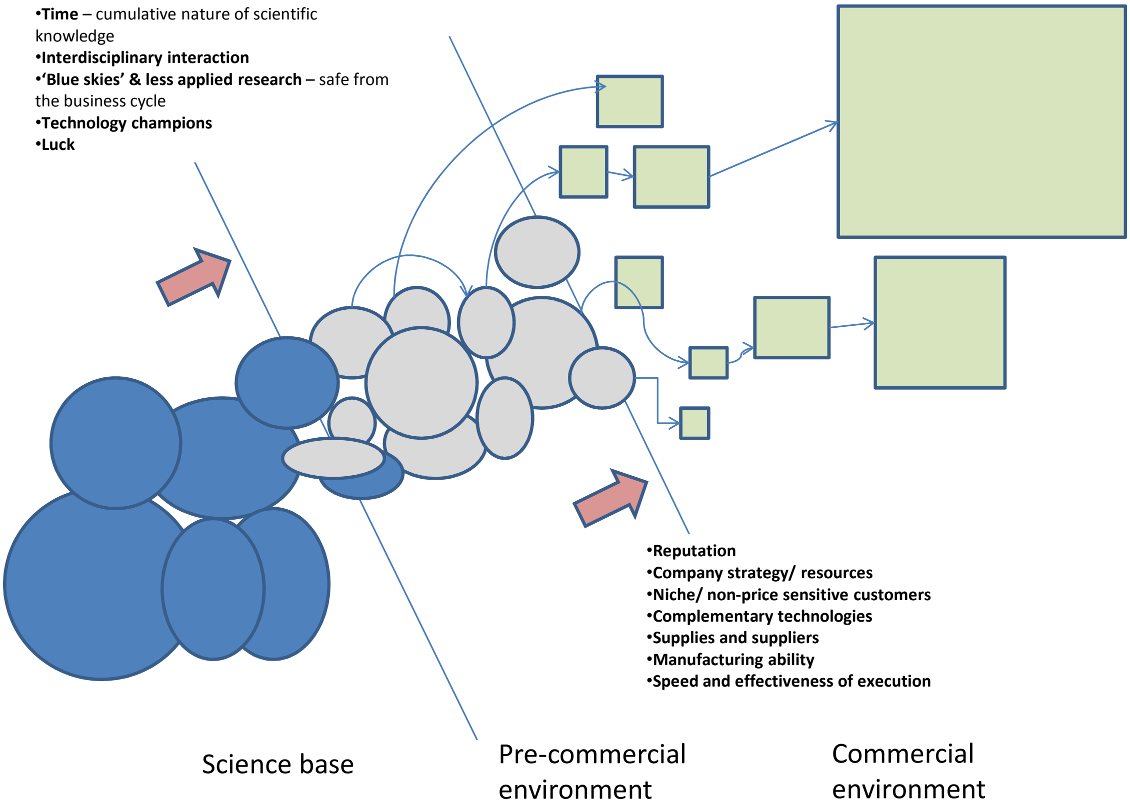

Figure 5 Technology emergences from lab to market

4.2 How does the UK perform in the commercialisation of breakthrough technologies?

Assessing the performance of the UK in science-based commercialisation is difficult even in the technologies we have examined. Breakthrough technology development is a global phenomenon involving actors from many countries. The case studies highlight numerous examples of UK participation; in particular UK organizations played a major role in the commercialisation of liquid crystal displays, optical fibres, light emitting diodes (particularly organic light emitting diodes) and Continuous Inkjet printing (CIJ). The UK continues to show technology leadership in CIJ and emerging elements of the LCD industry (for example Zenithal Bi-stable LCDs) and the LED industry (continuing in organic LEDs).

Achievement in these areas however needs to be set against the initial established criteria of success. Taking the example of the LCD industry, it is true that the UK government (through military research, grants and contracts) invested in the development of liquid crystal materials in the 1960s and 1970s. This led to a dominant position in the global supply of liquid crystal materials and the creation of key intellectual property relating to twisted and super twisted nematic structures. However, the UK's (through British Drug House (BDH)) global position in materials was overtaken by another European counterpart, and eventual parent firm of BDH, Merck, which still holds this position today.

In this case we could say that the LCD industry was a missed opportunity for the UK, but the UK LCD industry was primarily focused on military customers; highly specialized applications, low production quantities and high per unit costs. This meant that the UK LCD industry was never in a competitive position to enter the consumer display/ electronics market. Whether we can call this a failure of UK technological commercialisation is difficult to say, when success in the consumer market was never the aim of the UK research programs, rather superior military applications, which were delivered.

Comparing the LCD industries in the UK and the USA we can say that for $ amount invested in this technology the USA lost out more on their LCD programs. Extensive funding; from early R&D programs at RCA in the 1960s through to the Advanced Displays research program of the 1990s, still resulted in no long standing technological leadership or industry in LCDs in the USA. The ability of public policy to support long standing technology leadership in a breakthrough technology field is in need of further research. The cases show numerous examples of policy assisting in the creation of technology leadership, but the leadership is not sustained for a period long enough to also capture adequate value from the initial leadership.

Not capitalizing on technological leadership is also shown in the case of optical fibres. UK organizations were at the forefront of the majority of technological innovations that led to the development of optical fibre communications. As the following quote from Hecht (2004) sums up; "…To the American communications industry, fibre optics was at best a vague hope from some distant future. It had no obvious connection with near term trends…The British were the wild-eyed optimists" (p.161). The 2009 Nobel Prize for physics to Charles Kao for his work on optical fibres in the 1960s at Standard Telecommunications Labs and David Payne of Southampton University's Millennium Prize in 2008 for erbium-doped fibre amplifiers, attests to this further.

The British Post Office, which in the 1960s had the responsibility for communications services in the UK, largely initiated and supported the scientific and technical advances made in optical fibres in the UK. Their role was critical in accelerating development by providing seed funding for research programs, bringing together the science and advanced techniques of glass manufacturing and telecommunications research, and creating industrial panels to assess and test the resulting equipment.

The first fibre optic communications network was established at Dorset in 1975, less than a decade after Kao and Hockman presented their radical theoretical thoughts on the potential of fibre optics as a communications medium[23]. So what happened to the 'wild-eyed' optimists? Telecommunications deregulation worldwide, and particularly the restructuring of the British Post Office in the late 1970s and then privatization of their telecommunications function in 1982 played a large role. It highlights, what must be acknowledged in the all the breakthrough technology cases analyzed, the effect of the macroeconomic, social and political environment on the development of technology.

In addition, the organizations involved in the pre-commercial development of the technology including; the Ministry of Defense Royal Radar and Signals Establishment (RSRE), the British Post Office Research Labs at Dollis Hill, Standard Communications Laboratory at Harlow (a subsidiary of US based International Telephone and Telegraph (ITT)), Southampton University's optoelectronics research group; could not provide the 'mission driven' research environment to take the technology through the pre-commercial to the commercial environment, or were not in a position to execute on

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[23] Kao and Hockman stated in their 1966 paper that optical fibre communications could be commercially feasible if the attenuation rate in the fibre (light loss) could be reduced to 20dB per KM. In 1966 the attenuation rate of fibres was 1000dB per KM.

the technologies potential in the commercial environment, either because of ownership issues, ownership changes (e.g. STL) or other re-organization (e.g. BPO).

Ownership structures and changes also feature in the CIJ case. The UK maintains a dominant global position in continuous inkjet technology, through a cluster of firms located in the Cambridge area. These firms can trace their linage either directly, or through senior management back to the technology consultancy Cambridge Consultants (CCL). CCL conducted research and development activity (sponsored by chemical company ICI) in the late 1970s and developed technological leadership in the CIJ field. This leadership was exploited through the creation of a number of spin-out firms over the next two decades, encouraging the CIJ cluster that now exists in Cambridge.

The inkjet printing case study provides the most extensive examples of the use of equity funding for technology development of the cases analysed. Related to this use of equity funding is ownership changes; from the 1970s until the present day there have been a number of ownership changes in UK CIJ firms including recent (post 2000) acquisition activity by a major Japanese based conglomerate of three UK based CIJ firms. Ownership changes alter the development and commercialisation trajectory of these technologies. Ownership changes can move the technology into the commercial environment by providing resources (financial, marketing, human) and pathways to market (access to supply chain), all of which could accelerate development. Change of ownership also alters the pathway and structure of value and employment creation of the technology and in such a way that adequate benefits may not accrue to those who supported the technology previously.

This discussion of UK performance in the commercialisation of breakthrough technology highlights three conclusions. Firstly, the context of national programs of research in breakthrough technologies has a strong influence on the eventual commercial outcomes of the research; in the LCD case the goal of UK research programs was not consumer electronics production (as it was in South Korea and Taiwan) but (the much narrower) goal of superior and specialized military applications. Such a context shapes the eventual commercial outcomes of the research as commercialisation resources evolve out of this attitude. In the case of LCD technology, the goal was not consumer applications therefore resources were not directed into creating links with electronics firms or the production and manufacturer of materials beyond the LC materials. This is not the same as picking winners, but by allowing resources and ability to develop in a national context beyond early and niche areas, capturing the broader value and employment creation effects of a breakthrough technology may be possible.

Secondly, the importance of the role organizations play in hosting pre-commercial development and pushing it through to the commercial environment is highlighted. To successfully commercialize breakthrough technology organizations' need either both pre-commercial and commercial technology development ability and resources, or the ability to transfer the technology from one organization to another in order to provide this ability and resources.

Thirdly, breakthrough technology, because of its long timelines of development and potentially revolutionary industrial effects, will be influenced by macroeconomic, social and political factors in expected and unexpected ways. This means that policy activity aimed at accelerating technology commercialisation will have to be long term but, pro-active in some circumstances and responsive in others. Such a need for flexibility in policy will require ongoing two way communication between the policy, industrial and scientific communities.

4.4 Public policy implications for the UK

The aim of this research is to understand the process of commercialisation of breakthrough technologies from the science base to viable commercial applications, through the lens of how this process is funded. This research contributes to the commercialisation activities of the CIKC by providing evidence and informing commercialisation trajectories of past breakthrough technologies, particularly in regards to funding strategies. This in turn allows us to interpret the current advances in Photonics and Electronics within the recent history of breakthrough technology emergence and it is in this sense that the following policy implications are offered.

The earlier conclusions highlighted that the breakthrough technology cases were stories of people, by more specifically the interaction of people. The importance of multi-disciplinary teams and of close networks of scientists working on problems is demonstrated time and time again by our cases. The technologies examined did not rely solely on any single breakthroughs but successive breakthroughs and these advances frequently came from unexpected sources, sometimes by people working on unrelated problems.

The creation of multi-disciplinary teams working in close proximity is likely to be more effective than individuals working in isolation. This should be recognised in the delivery of public support.

The case studies show the importance of creating environments beyond university research laboratories, where pre-commercial technology can not only be developed but also pushed through to the commercial environment. The cases showed many examples of private firms with these environments; Bell Labs, STL, RCA. There were also examples of other organisations, both public and private, that provided environments supportive of pre-commercial technology and then transitioned this technology into other organisation for commercial exploitation; for example CCL transitioning CIJ technology to its spin-outs for exploitation, RSRE transitioning LC material to BDH.

Innovation policy should include the active creation and support of this type of environment

The importance of government R&D contracts at the earliest stages of the development of new technology is evident. In the United States the SBIR programme plays a significant role by establishing R&D support as commercial contracts (a similar, but very much smaller example of this can be found in the research consultancies in the Cambridge area). The ability of the SBIR programme to provide second-stage, higher, funding is also important.

The UK should adopt the SBIR model and the Government should give more support to the Technology Strategy Board to expand the current efforts in this area.

Public sector procurement of new technology products is also very important. Our cases reveal a number of examples where ‘deep-pocket’ procurement (e.g. defence, space, energy) was vital in providing early revenue and allowing companies to travel down the production experience curve and capture economies of scale.

Public procurement policy should support innovation policy and wherever possible provide first use demand for innovative products.

Our case studies reveal the long time horizons and very uncertain nature of early research and development progress with breakthrough technologies. This makes picking winners impossible, and means that patient and consistent support is required. The limits and abilities of the current venture capital model must also be recognised. Venture capital can only support technology in the commercial environment and will need to realise their investment (i.e. trade sale or IPO) in this technology in a 5-7 year time period[24].

Early stage, publicly backed venture funds can play an important role at the early commercial stage, but changes are needed to their current structure. In particular, the size of these funds (typically around £30m) and their time frame (typically 10 years) both need to be increased in order to respond to the long development times of new technology in tackling both the technology and the market development.

Early stage venture funds will only rarely take new technology through to a stage where real value can be extracted from it through revenue, or the attraction of significant new investment. This means that those showing the greatest promise should be able to obtain further funding, possibly through the recently announced Strategic Investment Fund. This fund of funds approach could combine public and private funds in support of the best prospects emerging from early-stage funding and prevent their premature sale.

The Strategic Investment Fund should be at least £1bn in size and integrated into the early stage public funding structure.

The case studies show the importance of government policies beyond those that would be called innovation policies in the commercialisation of breakthrough technology. Major government commitments (e.g. space, energy, military) can, and should, provide a major stimulus to innovation and both would benefit from greater integration.

Innovation policy should be part of a wider strategic industrial policy. This should attempt to ensure that policies aimed at supporting the development and commercialisation of new technologies are reinforced by other policies (e.g. taxation, energy pricing), standards and regulations.

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[24] Fund lifetimes under the dominant Limited Liability Partnership model of venture capital are typically ten years, but fund start-up time, deal flow investigation at the beginning of the fund lifetime and the need to establish early returns to the fund to establish a track record for the fund team from approx year 7 onwards means that the actually portfolio firm development time ranges from 5-7 years.

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