Funding Breakthrough Technology

Case summary : Light Emitting Diodes

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This case summary is part of the 'Funding Breakthrough Technology' project. This project is in the commercialisation stream of activities of the EPSRC funded Cambridge Integrated Knowledge Centre (CIKC) in photonics and macro molecular material. Historical case studies of eight breakthrough technologies of the last 60 years are being investigated with the specific focus of how these technologies were supported and finance in their journey from the lab to market. The other case studies are Photovoltaics, Liquid Crystal Displays (LCD), Inkjet printing, Fibre optic communications, Giant Magnetoresistance (GMR), Micro electronic mechanical systems (MEMS) and Computed Tomography (CT) and Magnetic Resonance Imaging (MRI).

This case study was completed by Rehana Khanam as part of her fourth year Masters of Engineering (MET) long project under the supervision of Andy Cosh and Samantha Sharpe. All of the case study documents are works in progress. If you would like to comment on any of the case study summaries please contact Dr. Samantha Sharpe at the Centre for Business Research on email (s.sharpe@cbr.cam.ac.uk) or telephone (+44 (0) 1223 765 333. As these documents are works in progress we would request that the case studies not be cited without the author's permission.

Introduction

Light-Emitting Diodes (LEDs) are semiconductor devices that emit light when the diode is switched on:

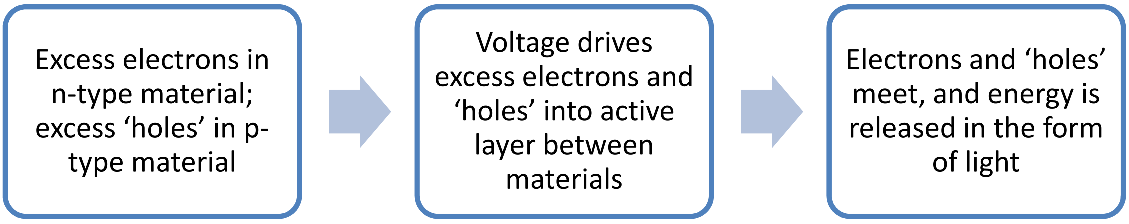

Figure 1: Basic science for light-emitting diodes

The various generations of LED may be differentiated by the material in the active layer of the diode.

Traditional LEDs are an established technology with many diverse applications ranging from bicycle lights to display monitors. The advantages over traditional light sources are numerous: smaller size, higher energy efficiency, longer lifetimes and a greater degree of robustness.

Organic LEDs (OLEDs) use organic materials with a specific type of bond (pi-bond) as the emitting layer of the diode. This material is commonly a polymer which has the added prospect of allowing flexibility. OLEDs are a more technologically advanced form of LED with a range of applications such as displays for digital cameras and mobile telephones. The advantages over standard LEDs are a lighter component, higher energy efficiency and, if polymer, the versatility associated with a flexible material. OLEDs are commonly used in display technology – the advantage over Liquid Crystal Displays (LCDs) is that a back-light is not required, thus there is substantially less power consumption. Also, OLED displays may be even thinner than LCDs.

Gallium Nitride (GaN) LEDs are a further development in this field. Such LEDs commonly emit blue light but may be modified to emit alternatively coloured light e.g. white. The ability to emit white light is a key development - LEDs may be used to replace the ubiquitous light bulb. A popular application of blue LEDs is in Blu-Ray digital versatile discs or in games consoles. GaN LEDs are relatively new compared to the more traditional LEDs. Advantages (over older LED technologies) such as the choice of light colour emitted as well as the ability to withstand higher temperatures mean GaN LEDs have the potential to become increasingly disruptive technologies in the future.

GaN LEDs have been commercialised to some extent but the key obstacle to achieving higher market share has been cost. The breakthrough technology in question seeks to produce low-cost GaN LEDs that are superior in performance and efficiency compared to other lighting sources but with the qualifying attribute of being affordable.

The report commences with analysis of successful and unsuccessful commercialisation routes taken by the more established technologies of LEDs and OLEDs. Key factors influencing the success or failure of ventures will be determined with a particular focus on the role of funding in the commercialisation of these technologies.

Research into the current state of GaN LED commercialisation will be undertaken with emphasis on identifying key tools required for capitalising on low-cost production techniques.

The key goals of the project are thus:

- To use the learning gained from the commercialisation of emerged technologies to propose typologies for pathways to market for LEDs
- To inform the commercialisation effort of low-cost GaN LEDs such that opportunities for success become a reality

A framework for investigation was used, based on the vital areas requiring development in the drive for commercialisation:

- **Technology:** An analysis of the technology's progress towards market, both in terms of its production and processing development.
- **Market:** Identification and analysis of potential markets and the impact of markets on the development path for the breakthrough technology.
- **Funding:** Discussion of how funding enabled or limited the commercialisation of the breakthrough technology.
- **Key players:** Identification of key players in the development of the technology.

Section II uses this framework to discuss the case studies of past commercialisation efforts.

In section III, patterns will be drawn across the case studies using the following framework:

- **Precedence:** Identify if steeper gradients to commercialising new technologies exist due the lessons learnt in commercialising emerged technologies.
- **Obstacles:** Determine and analyse the obstacles that were and are prevalent in this area of breakthrough technology
- **Commonalities:** Identify other common themes in the commercialisation of these technologies e.g. legislative issues, societal trends
- **Typologies:** Generate funding typologies for this family of breakthrough technologies

Drawing inferences from prior work, a framework similar to that of section II will be used in section IV to inform the commercialisation efforts of low-cost GaN LEDs:

- **Technology:** Discuss how the technology needs to be developed from the potential of breaking through to actually disrupting the market and industry
- **Market:** Identify further markets/applications that may not have been envisaged at the time of initial innovation

- **Funding:** Explore the funding needs of the technology that will enable further successful commercialisations.
- **Key players:** Identify key players that will enable further successful commercialisations and suggest how their influence may be maximised

Finally, overall conclusions will be drawn for this area of breakthrough technology and further work to enhance the research will be proposed.

1. Case Studies of Past Commercialisations

1.1. Traditional light-emitting diodes (LEDs):

Traditional LEDs have been in existence for decades and are now almost a commodity – they are cheap, widely available and with many applications ranging from display monitors to low-end bicycle lights.

Attempts to commercialise first generation LEDs spanned four decades, preceded by incremental scientific developments in the laboratory. In the first-generation LEDs, three compounds – Gallium Phosphide (GaP), Gallium Arsenide Phosphide (GaAsP) and Aluminium Gallium Arsenide (AlGaAs) - were competing to be the emitting layer of the diode.

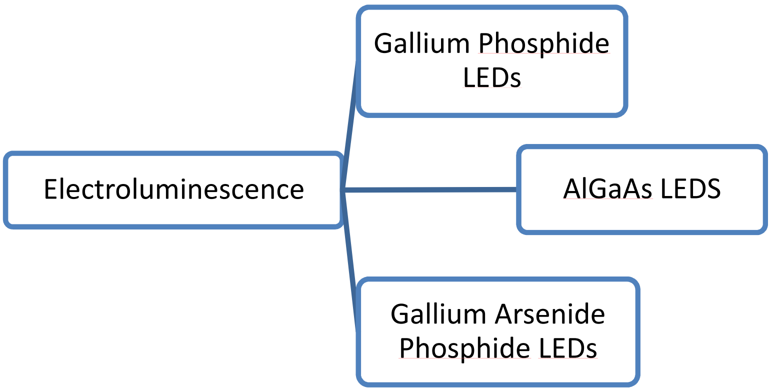

Figure 1: Competing materials for traditional light-emitting diodes

GaP LEDs saw some commercial success but were leapfrogged by LEDs with superior materials such as GaAsP and AlGaAs. Of the latter two, AlGaAs LEDs although arriving later to market ultimately proved more successful due to higher efficiency and more reliable performance.

A Brief History of the Early Science:

The possibility of LEDs came after H J Round's 1907 discovery of electroluminescence from a semiconductor – the emission of light from silicon carbide (Morton and Garbriel 2004; Grimmeis and Allen 2006; Zheludev 2007). H J Round was working for Marconi Laboratories and, despite a one-page article in *Electrical World*, no further investigations were carried out. Marconi were more focused on developing technologies closely linked to their core technologies in radio communications.

The first LED was reported in 1927 by Russian scientist Losev (Grimmeis and Allen 2006; Zheludev 2007) in *Wireless Telegraphy and Telephony* but the work went largely unnoticed by the wider scientific community. Following Losev's death during World War II, the work was lost for decades.

A pause on LED developments occurred in the first half of the 20th century with military R&D spending focused on developing radar and aerospace power as well as the Great Depression dampening the spending might of large corporations and governments alike.

Two post war developments stimulated interest in the field again. The first was Lehovac et al's finding (Zheludev 2007) of forward and reverse bias leading to distinct types of electroluminescence at the US Military Signal Corps Engineering labs in 1951. The second was Haynes and Westphal's breakdown of reasons for observed radiation at bell Labs in 1956 (Zheludev 2007). Research programs in the field of LEDS were soon underway at Philips, General Electric Company (GE) and Services Electronics Research Laboratories (SERL) in the UK.

Early work on electroluminescence was very much laboratory-based with discoveries fuelling subsequent technology breakthroughs/pushes. As the technologies were taken up by various companies and military-funded projects, it is apparent that market demand became a more decisive factor in technology improvement.

Gallium Phosphide LEDs:

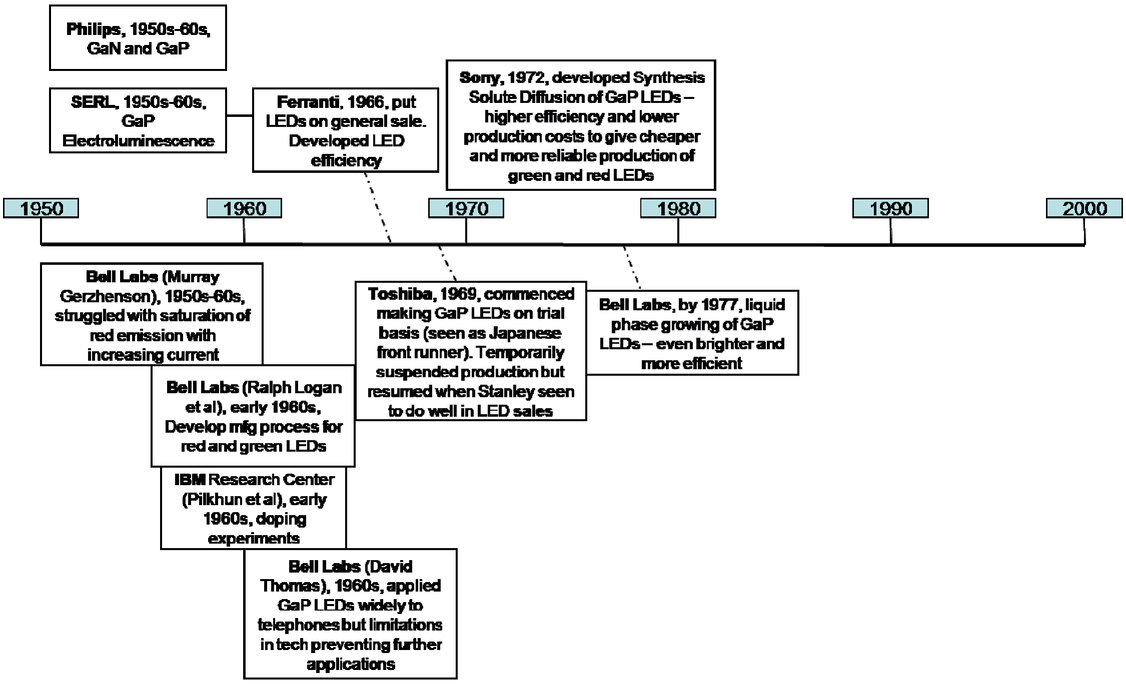

Figure 2: GaP LED timeline

In 1955, Wolff et al[1] reported electroluminescence of GaP in the visible spectrum (Zheludev 2007). Bell Labs and SERL subsequently pursued research in GaP which had sufficient potential for a viable light source in their intended applications. Philips embarked on a quest to replace light bulbs and sought alternative materials because white light emission required a greater energy gap than GaP could afford.

Philips considered Gallium Nitride to be a contender at this early stage but years of research and repeated failures to grow single and correctly doped crystals showed sufficient advances in materials research and growth technology had not been made to successfully develop Gallium Nitride LEDs. The Philips researchers returned to research in GaP and made progress in developing efficient enough LEDs through the 1960s. The project was moved into a bulb production factory in Eindhoven for 1.5 years but eventually terminated after this brief spell.

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[1] US Military signal corps engineering laboratories

SERL, part of the Royal Naval Scientific Service, pursued GaP LEDs from the outset and managed to successfully produce viable and sufficiently efficient devices known as 'crystal lamps' in 1962. These were retained for military use until 1966 when Ferranti Plc[2] was allowed to sell the LEDs to the general public. Ferranti made successive developments to the diodes, helping to increase efficiency and quality of production techniques.

The role of military funding was important; from the beginning, research and development was geared towards meeting specific applications and products for the military. We can say that the market for these LEDs was to some degree market pull; although the military market was small and highly specialised "pull" as opposed to that in consumer electronics markets.

Developments at Bell Labs in America occurred throughout the 1950s and 1960s (Johnstone 1999). Initially, Gerzhenson's team struggled with saturating red emissions with increasing currents but these issues were eventually overcome in order to allow development of manufacturing processes for both red and green LEDs in the early 1960s. LEDs produced were applied widely in Bells Labs' telephones helping develop a neatly integrated producer and user model for GaP LEDs in the 1960s. However, further applications were limited due to the telephone-focused design. In the late 1970s, Bell Labs attempted to develop more applications for GaP LEDs having achieved brighter and more efficient LEDs but the attempt failed as an alternative emitting material, GaAsP, had emerged as a superior substrate for LEDs.

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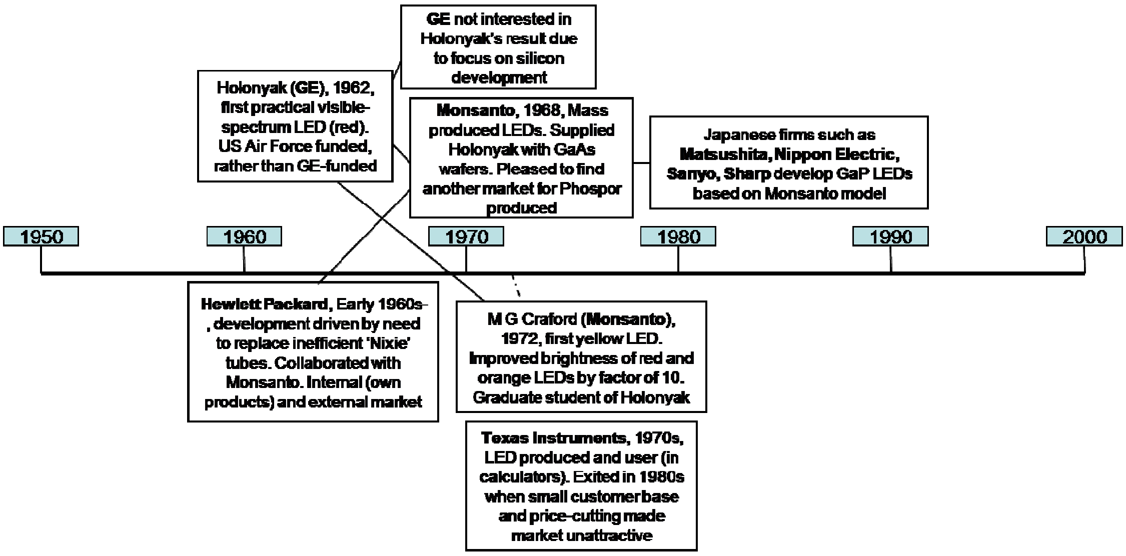
[2] Ferranti was founded in 1882 and became a major UK electrical engineering and equipment firm after surviving receivership in the early 1900s. During the Second World War Ferranti became a major supplier to the military of electronics; through their development of the Identification of Friend or Foe (IFF) system, an early precursor to radar systems. Their military work continued into the post war period, notably with the Air Force and instrumentation on helicopters and jets. Ferranti was an early European pioneer of semiconductor materials; they were the first European firm to create a silicon diode in 1955. Ferranti eventually sold their micro-electronics activities to Plessay in 1988, just after their ill-fated acquisition of US firm International Signals and Control (ISC) in1987 and before the following fraud investigation and eventual bankruptcy of Ferranti International in 1993.

Gallium Arsenide Phosphide LEDs:



GE not interested in Holonyak's result due to focus on silicon development

Holonyak (GE), 1962, first practical visible-spectrum LED (red). US Air Force funded, rather than GE-funded

Monsanto, 1968, Mass produced LEDs. Supplied Holonyak with GaAs wafers. Pleased to find another market for Phospor produced

Japanese firms such as Matsushita, Nippon Electric, Sanyo, Sharp develop GaP LEDs based on Monsanto model

Hewlett Packard, Early 1960s-, development driven by need to replace inefficient 'Nixie' tubes. Collaborated with Monsanto. Internal (own products) and external market

M G Craford (Monsanto), 1972, first yellow LED. Improved brightness of red and orange LEDs by factor of 10. Graduate student of Holonyak

Texas Instruments, 1970s, LED produced and user (in calculators). Exited in 1980s when small customer base and price-cutting made market unattractive

Figure 3: GaAsP LED timeline

Work in GaAs and GaP substrates had suggested red wavelengths of light could be achieved; as a result, Nick Holonyak (a junior researcher at General Electric) (Johnstone 1999; Craford 2004; Schubert 2006) pursued GaAsP LEDs. Holonyak was building a device with light emission that was visible to humans and could therefore have mass market potential. In 1962, the scientific breakthrough arrived but to no real avail. The devices were expensive with few applications and were rejected by GE who was already committed to work in silicon devices. Here, a constraint to commercialisation was applied as further support/funding was not supplied by GE who could not envisage the future value of the device.

The GE project however was funded by the US Air Force and thus was not bounded by corporate confidentiality rules and patent restrictions, creating an open space to advance the science. Holonyak was allowed to collaborate with Monsanto Corporation (a chemicals company) which enabled the technology to be commercialised rather than halted by GE after the original scientific discovery. Unlike GE, Monsanto were spurred on by Holonyak's result and scaled up production of the GaAsP LEDs. Monsanto viewed the opportunity as a route into the electronics business, utilising the abundance of phosphor already possessed.

Hewlett-Packard (H-P) also played a key role in this commercialisation path of GaAsP LEDs. H-P had undergone extensive development work in scientific instrumentation and were driven to replace 'Nixie tubes' in their displays – the residual technology from earlier models that was incompatible with other devices in the displays. H-P collaborated with Monsanto to form a joint development programme (also funded by the US Air Force) to exploit H-P's knowledge of devices/systems and Monsanto's materials expertise. The collaboration worked well both from a technology development perspective as well as in terms of consistent funding. When initial production prototypes were demonstrated in 1965, Bill Hewlett (Chief Executive Officer of H-P) wholeheartedly committed the company to supporting full commercialisation. Display technologies were identified as a key application area and the collaboration rushed to embed GaAsP LEDs in devices such as hand-held calculators.

The path to successfully commercialising GaAsP LEDs was not linear. Holonyak's research at GE was funded by the US Air Force. Like SERL's development of GaP LEDs, here is an example of military-funded product-focused research coming to fruition. Furthermore, there is an evident gap between the pursuit of scientific research funded by the military and the drive to exploit wider commercial markets – here, the gulf being overcome by support from a visionary CEO.

Followers such as Matsushita, Nippon Electric, Sanyo and Sharp later entered the market by selling GaP LEDs based on Monsanto's product.

During the period where Monsanto was scaling up production and Holonyak was consulting for the organisation, Holonyak sent some of his graduate students to assist.

Amongst them was M George Craford (Craford 2004; Morton and Garbriel 2004) who, in 1968, developed a yellow LED by doping GaAsP with nitrogen. The work was not pursued by Monsanto whose marketeers found customers only wanted cheaper LEDs, not new colours. Although Monsanto was keen to develop and commercialise red GaAsP LEDs, further funding was not committed to yellow LEDs. Arguably, Monsanto's response was market-focused and thus well-founded but, on the other hand, the very nature of breakthrough technologies means that the market may not immediately see relevant applications and the value of a technology. Thus, it is worth being open to innovation so that opportunities to create new products, markets and applications are not missed.

By the late 1970s, Monsanto withdrew from the GaAsP LED business as, although the technology had surpassed alternative materials' performance (e.g. GaP LEDs), they could not compete with liquid crystal displays – a substitute technology – nor with competitors within the GaAsP LEDs market. A key competitor identified was Texas Instruments (Johnstone 1999) whom, like Bell Labs in GaP LEDs, initially created a neat vertically integrated model. The overall GaAsP LED market size was limited and being eroded by LCDs. As more entrants arrived (including the aforementioned 'followers') price squeezes made the business uncompetitive and Texas Instruments also withdrew. The strongest players in the LEDs were exiting the market, leaving an opportunity for a high-performance, differentiated product to capture the market share; a gap filled by Stanley Electric and their AlGaAs LEDs.

AlGaAs LEDs:

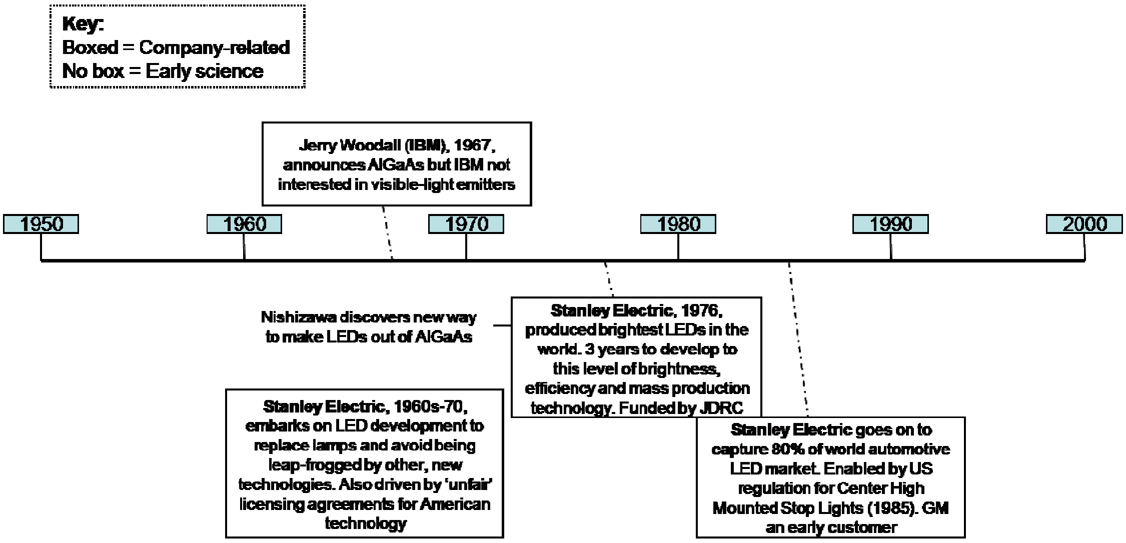


Figure 4: AlGaAs LED timeline

Although numerous Japanese companies followed Monsanto Corporation in commercialising GaAsP LEDs, Stanley Electric embarked on its own grass-roots research programme [**4**]. Stanley had seen success in the 1950s-60s as the major supplier of lights to Japan's booming automotive industry but suspected this position was indefensible against incoming LED technologies that were being developed in the USA. Stanley originally chose to license the technology from an American start-up claiming to produce LEDs akin to those of Monsanto. The start-up failed to deliver on its promises and Stanley were left without a supplier for LEDs. Other licensing agreements with American companies were ruled out as they were deemed extortionate in cost.

In 1967, Jerry Woodall, an electrical engineer at IBM (Johnstone 1999) announced AlGaAs as a potential light-emitting source. The host corporation, however, was not interested in visible-light emitters and chose not to pursue the finding. This lack of interest eventually turned out to be a poor decision and again presents the difficulties in understanding/imagining the potential of new technologies at the discovery phase.

Woodall's announcement was capitalised upon by Nishizawa, a freelance Japanese inventor, who developed the viability of commercialisation by finding appropriate production methods for AlGaAs. The transfer to Stanley Electric for mass production was funded by the Japanese Research and Development Corporation who provided approximately £1.3million from 1972-1976[3].

The transfer of technology from laboratory to mass production is a difficult and risky task so the support of the JDRC must be recognised as enabling this key transition. The move was a success and Stanley eventually became dominant in the automotive lighting market. By 1980, major players in the LED market such as Monsanto and Texas Instruments had exited the market due to competitive and crippling price-cutting, allowing Stanley to capitalise on their customer base. Stanley embarked on market diversification e.g. advertising billboards, pinball machines; gradually exploring multiple applications of their single breakthrough innovation.

In 1985, exterior lighting on cars presented a huge market for expansion as regulations for Centre High Mounted Stop Lights were implemented in the USA. Stanley Electric designed towards this lighting system in a joint development with General Motors and, by leveraging existing relationships with automobile manufacturers, Stanley managed to achieve an 80% market share. A mix of market creation by legislation and advantageous use of reputation were instrumental in this particular commercialisation path.

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[3] Albeit reluctantly due to the associated risk of transferring an unproven technology, source www.jst.go.jp/itaku/results50then.pdf, accessed June 2009.

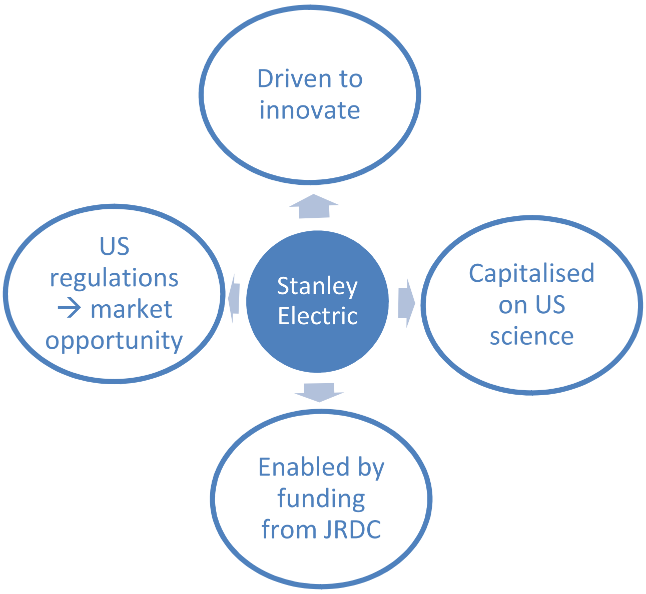
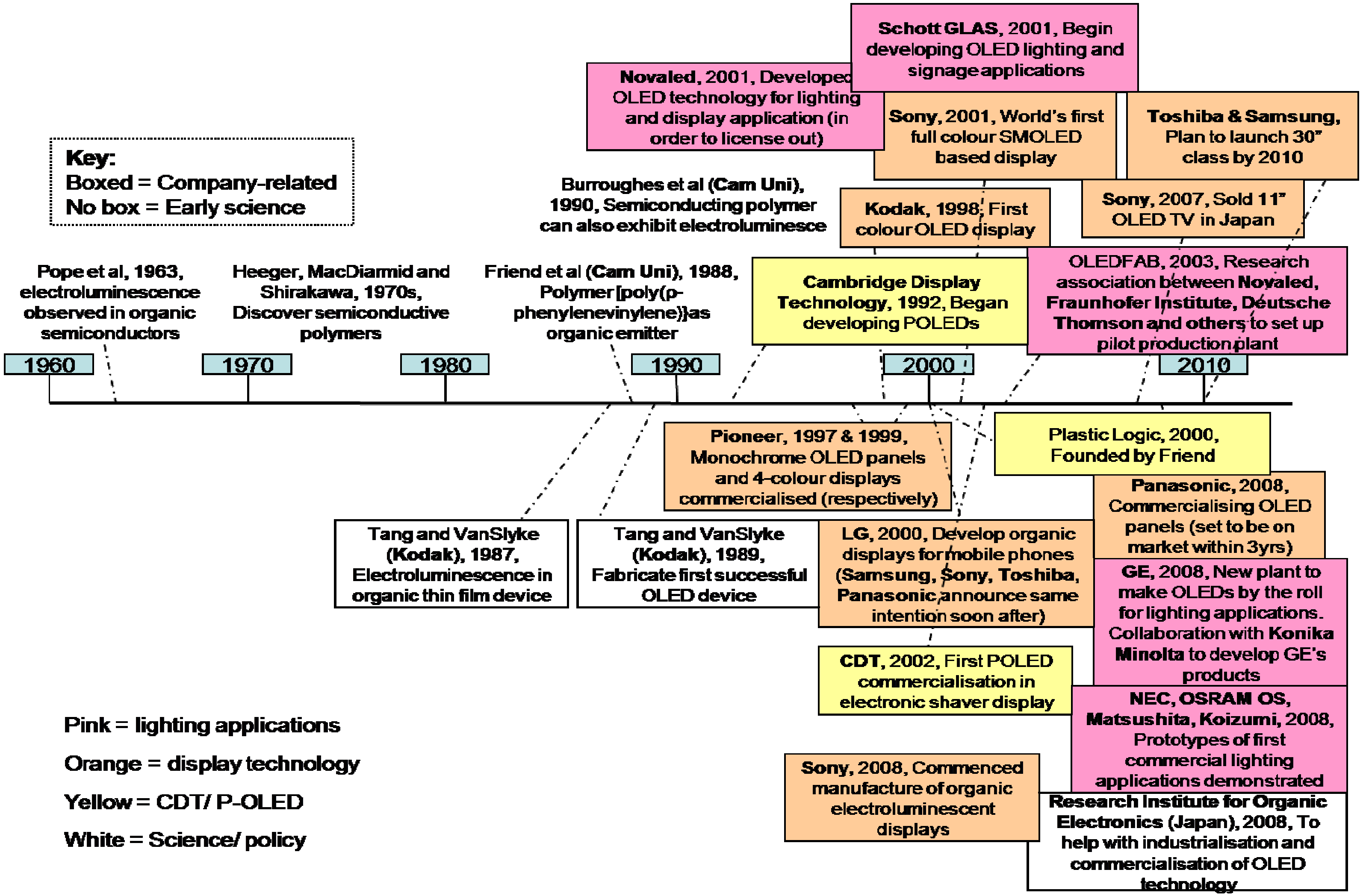


Figure 7: Factors affecting Stanley Electric's market entry

1.2. Organic Light-Emitting Diodes (OLEDs):

The commercialisation of OLEDs has been somewhat faster than with traditional LEDs. After Pope et al's observation (Borchadt 2004; Morton and Garbriel 2004) of electroluminescence in 1963, Heeger, MacDiarmid and Shirakawa's work (Braun 2002; Borchadt 2004) on conductive polymers in the 1970s laid the foundations for an emerging technology with potential in w
currently dominate the market - Small Molecule (SMOLED) and Polymer (P-OLED). Both have been applied in varying technologies and it is not yet apparent which will be most successfully commercialised in the longer term. Instead of being in competition, the variants may even succeed equally, but in differing areas of the lighting and display markets.

Figure 6: Timeline for Organic LED commercialisation



Key:
Boxed = Company-related
No box = Early science

Pope et al, 1963, electroluminescence observed in organic semiconductors

Heeger, MacDiarmid and Shirakawa, 1970s, Discover semiconductive polymers

Friend et al (**Cam Uni**), 1988, Polymer [poly(p-phenylenevinylene)]as organic emitter

Burroughes et al (**Cam Uni**), 1990, Semiconducting polymer can also exhibit electroluminesce

Novaled, 2001, Developed OLED technology for lighting and display application (in order to license out)

Schott GLAS, 2001, Begin developing OLED lighting and signage applications

Sony, 2001, World's first full colour SMOLED based display

Toshiba & Samsung, Plan to launch 30" class by 2010

Kodak, 1998, First colour OLED display

Sony, 2007, Sold 11" OLED TV in Japan

Cambridge Display Technology, 1992, Began developing POLEDs

OLEDFAB, 2003, Research association between **Novaled**, **Fraunhofer Institute**, **Deutsche Thomson** and others to set up pilot production plant

Pioneer, 1997 & 1999, Monochrome OLED panels and 4-colour displays commercialised (respectively)

Plastic Logic, 2000, Founded by Friend

Tang and VanSlyke (**Kodak**), 1987, Electroluminescence in organic thin film device

Tang and VanSlyke (**Kodak**), 1989, Fabricate first successful OLED device

LG, 2000, Develop organic displays for mobile phones (**Samsung**, **Sony**, **Toshiba**, **Panasonic** announce same intention soon after)

Panasonic, 2008, Commercialising OLED panels (set to be on market within 3yrs)

GE, 2008, New plant to make OLEDs by the roll for lighting applications. Collaboration with **Konika Minolta** to develop GE's products

CDT, 2002, First POLED commercialisation in electronic shaver display

NEC, **OSRAM OS**, **Matsushita**, **Koizumi**, 2008, Prototypes of first commercial lighting applications demonstrated

Sony, 2008, Commenced manufacture of organic electroluminescent displays

Research Institute for Organic Electronics (Japan), 2008, To help with industrialisation and commercialisation of OLED technology

Pink = lighting applications

Orange = display technology

Yellow = CDT/ P-OLED

White = Science/ policy

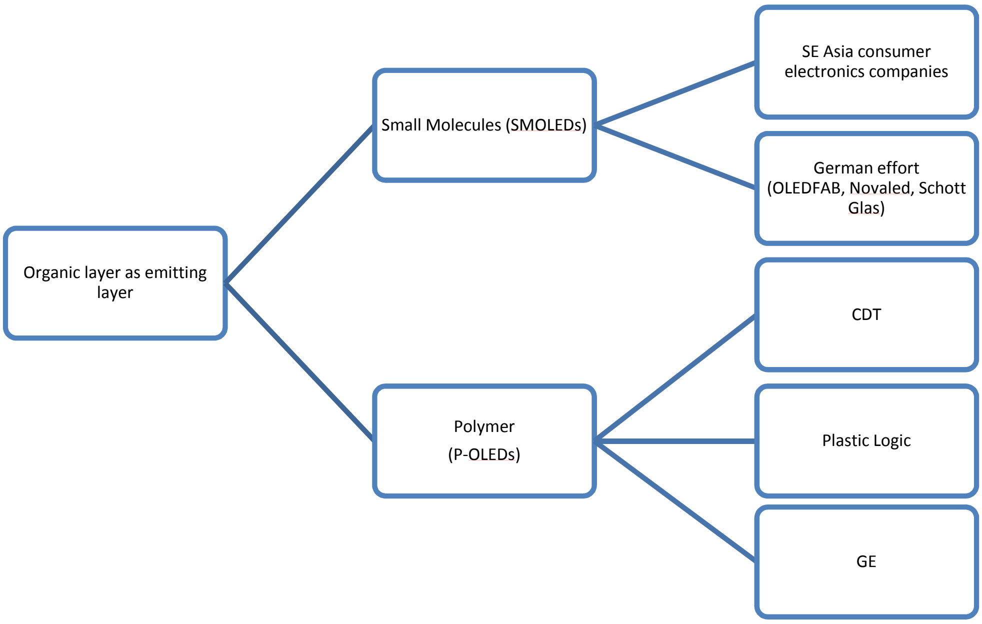


Figure 2: OLED types

Small Molecule Organic Light-Emitting Diodes:

In 1987, Tang and VanSlyke of Kodak (Braun 2002; Krasnov 2003; Borchadt 2004; Morton and Garbriel 2004) demonstrated efficient but low voltage light emission from a thin film device and went on to fabricate the first successfully working OLED. The Kodak researchers are regarded as the pioneers of SMOLEDs and emergence commenced with a technology push as the researchers sought to test the boundaries of known science. In 1998, via collaboration with Sanyo, Kodak released the first colour OLED display, indicating the viability of SMOLEDs in display technology. Further commercialisation was achieved via licensing activity as market pull factors saw other organisations realising the benefits of using SMOLED technology.

Korean consumer electronics firm LG developed the first OLED-based mobile phone display in 2000(Tseng, Cheng et al. 2009). This event was closely followed by rivals such as Panasonic, Toshiba, Sony and Samsung announcing similar plans(Tseng, Cheng et al. 2009). Such displays are becoming commonplace in today's mobile phone market with bright, clear OLED displays allowing for slim line phones – device compaction being a selling feature.

SMOLEDs also featured in Sony's full colour OLED display(Braun 2002; Krasnov 2003) which was demonstrated in 2001. Sony commenced research in the area in 1994 and released its first full OLED application – an 11” television – in 2007. The television, although said to offer excellent performance in the general press, failed to capture the market due to high price[4]. The 13 year development period may be perceived as particularly long considering the scale, skills and experience afforded by Sony – the slow and unsuccessful commercialisation is blamed on the high cost of sourcing reliable and high-quality materials. In this case, funding was less of a constraint to the organisation than the availability of required materials.

Large Japanese corporations such as Panasonic, Toshiba[5] and Sony[6] are close to releasing large scale (e.g. 30”) display televisions in the coming years. Such televisions will be positioned in the same market as existing LCD televisions but with the added benefits of less power consumption (due to no backlight), thinner displays, higher contrasts and wider viewing angles but at more affordable prices (unlike Sony's first offering in 2007). The Japanese Government’s Research Institute for Organic Electronics has been set up to help with the production scale-up, materials sourcing and overall commercialisation of OLED display technology. This focused effort is further proof of the country's intention to capitalise on this breakthrough technology.

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[4] Especially relative to liquid crystal display [LCD] televisions, whose performance is seen to be a vast improvement on past display technology anyway.

[5] http://www.smarthouse.com.au/TVs_And_Large_Display/OLED_TV/D2B2X6P6

[6] http://www.electricalsolutions.net.au/articles/27388-2-11-the-year-of-OLED-lighting

OLED collaborations were also instigated in Germany. OLEDFAB was started in 2003 as collaboration between the Fraunhofer Institutes, Deutsche Thomson and other companies in order to set up a pilot production plant for OLED technologies. The collaboration was funded by $3.9million from the German government, and the research association seeks to make best use of the semiconductor technology expertise developed in East Germany during the Cold War and gear it towards a coherent effort in making Germany a world leader in OLED technology. The first signs of success arrived with the birth of Novaled in 2003, a spin-off from the Fraunhofer Institutes. The start-up received venture capital funding of 5.75million Euros (approximately $7million) and is continually developing OLED technologies for lighting and display applications in order to build a licensing business model. Its technologies have appeared in handheld computers and PDAs. Other leaders in the German push for commercialising OLED technology are Schott Glas and Osram who will undoubtedly benefit from the government-enabled OLEDFAB collaboration.

Polymer Organic Light-Emitting Diodes:

Soon after Tang and VanSlyke's seminal work on SMOLEDs, Richard Friend et al(Borchadt 2004) from the Cavendish Laboratories at Cambridge University found that polymer [poly(ρ-phenylenevinylene)] could also be used as the organic emitter for a light source. A further breakthrough came in 1990 when Burroughes et al (from the same laboratory)(Braun 2002; Krasnov 2003) added semiconductor polymers to the list of light-emitting sources. These pieces of work formed the foundation for Polymer Organic Light-Emitting Diodes (P-OLEDs).

The story of two Cambridge-based attempts to commercialise the research emerging from the laboratories of Cambridge University is relevant. Both Cambridge Display Technology and Plastic Logic were borne out of the Cavendish Laboratories but their offerings are different and it remains to be seen which will be the more successful.

CDT – a Cambridge success?

Cambridge Display Technology was founded in 1992 by Richard Friend and others to develop and commercialise in the field of P-OLEDs. The venture was originally funded by Cambridge University and Cambridge Research and Innovation Limited.

CDT's initial strategy was to manufacture component products for applications such as flat panel displays however this was revised when the cost and domination of global firms involved in these applications was realised (Maine and Garnsey 2006).

The business model therefore switched to an IP licensing model where revenue was achieved from licensing and royalties from partners such as Philips who use CDT's patents in order to implement P-OLED technologies in their own products. The licensing/royalties model presents an interesting method for commercialising new technology as the risk associated with production scale-up is decoupled from the technology company. The risk is instead associated with progressive research and development (R&D) and intellectual property (IP) ensuring steady (ideally, growing) revenues. The IP will only generate revenue if it meets the market pull channelled via partners who may be able to apply the new technology.

The business model evolved in 2000; in order to increase the attractiveness of their licensing agreements CDT returned to its initial strategy of small scale pilot manufacturing to demonstrate the viability of their breakthrough technology (Maine and Garnsey 2006). CDT saw its first application in the display for a Philips electronic shaver in 2002 and despite revenues which have grown (on the whole), the losses made each year mean survival is dependent on the injection of shareholders' funds.

In 2004, the company was floated on the NASDAQ and in 2007 it was acquired by Sumitomo Chemical Company, at a loss to the original investors. Year on year, CDT had been spending heavily on R&D with funds raised from shareholders being used to cover these expenses.

This Cambridge venture, despite being a source of exciting and innovative technology, has seen poor financial performance and, due to being sold at a loss to Sumitomo, may be seen as a failure for the UK's effort in commercialising technology.

Plastic Logic – a future winner?

Plastic Logic was also founded by Richard Friend and other in 2000 as a further spin-out. The company has progressed using a similar licensing/royalties model to CDT but with future aims to manufacture products using the company's own proprietary technologies. Plastic Logic's IP lies in production processes for advanced P-OLED materials, particularly in the sphere of low-cost printing of electronics.

The product under development at the moment is due to reach the market in 2010. The eReader is an electronic reader that can be used to view content such as books, journals and newspapers as well as a tool to read and annotate documents such as pdfs or word processing files – the device will be open format. A key aspect of the product is the flexibility of P-OLEDs that allows the eReader to be rolled up and stored in a small space, theoretically eliminating the need for cumbersome books or paperwork. The eReader needs to be launched fast, in order maximise market share and respond to competitors' offerings which have already been launched. Amazon's Kindle and Sony's Reader have technologically inferior features – lacking flexibility and open formatting. Plastic Logic's eReader should prevail in the marketplace but only if it enters the market soon enough to avoid the Kindle and the Reader gaining too many first-mover advantages.

Plastic Logic has developed its technology over the past decade using extensive venture capital funding (over $200million). A further $100million was secured in 2007 to build a production plant in Dresden – a signal of the commitment to build a product and production-based model, alongside licensing. The choice of location was reliant on multiple factors; first capitalising on Eastern Germany's electronics technology expertise (as aforementioned, with OLEDFAB), the local abilities in building the necessary infrastructure quickly and, finally, the subsidies offered by German authorities. The offer of financial support is important; growing companies are most at risk from weak cash flow and a lack of money to invest wisely, at the opportune moment. Consistent financial backing will always be instrumental in helping to secure successful commercialisations.

It remains to be seen if Plastic Logic will be a successful commercialisation story or if the slow development time necessary to develop such innovative technology will be a major pitfall for this promising young firm.

A key success story in the P-OLED market is GE. In 2008, the conglomerate announced the opening of a dedicated manufacturing plant to produce P-OLED lighting by the roll. General Electric had developed its products in collaboration with Konica Minolta who have, in turn, licensed the technology from Universal Display Corporation (UDC). The technology developed by UDC was enhanced by its past partnership with DuPont in developing efficient and fast production techniques for P-OLEDs. The benefit of this relationship was that it could combine UDC's high-performance P-OLEDs with DuPont's solution-based electronics printing process. The road to GE's commercialisation of P-OLEDs involved various key players but both the early science/production technology phase and subsequent product development phase required focused collaboration efforts in order to take the technology from the laboratory to the marketplace.

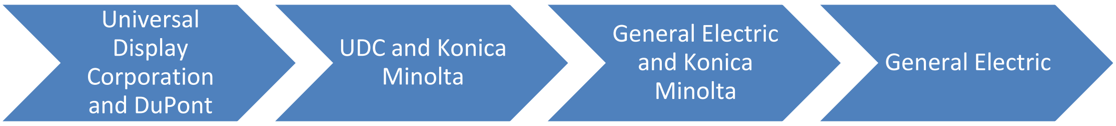

Figure 3: Chain of collaborations leading to GE opening OLED-dedicated manufacturing plant

So far, it is worthwhile to note that P-OLEDs have been commercialised by companies quite distinct from the originators of the technology. This is despite the originators being technology companies in their own right (i.e. profit-seeking), rather than laboratories embedded within universities or government/military organisations which are less interested in profit. The original technology push is somewhat distinct to the market pull – the pull being the factor which sees the technology actually being commercialised. In the P-OLED examples, these two ends are linked by collaborations/licensing activities. This is rather a stark contrast to the cases in traditional LEDs where the likes of Stanley Electric and Monsanto Corporation had more direct ties to the scientists developing the work.

1.3. Gallium Nitride Light-Emitting Diodes (GaN LEDs) so far:

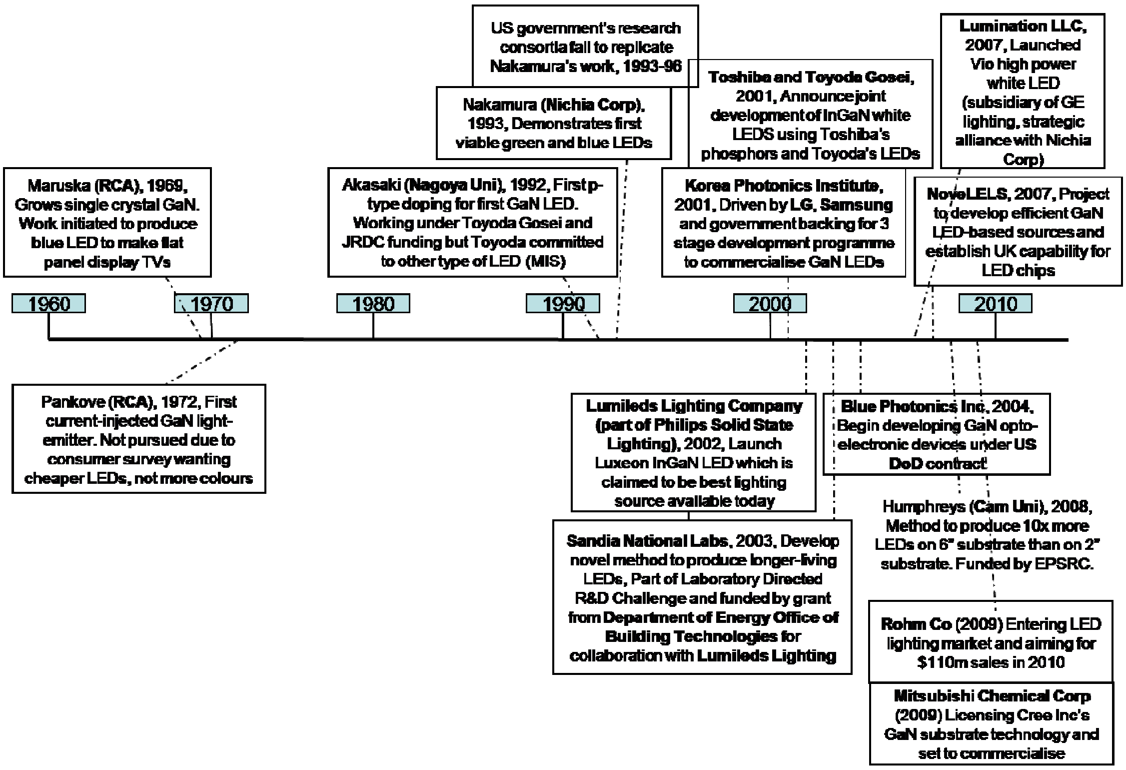

Figure 4: GaN LED timeline

The initial materials breakthrough for GaN occurred in 1969 when Herbert Maruska first grew single crystals of the compound(Johnstone 1999; Schubert 2006). Maruska was a junior researcher at Radio Corporation America. His work was commissioned by a more senior researcher (Tietjan) who desired a blue LED in order to make flat panel display television, decades before flat panel televisions actually entered the marketplace. The basis for Gallium Nitride research was thus based on anticipated market pull from the outset.

Maruska's breakthrough was furthered by Jacques Pankove (also of RCA) who demonstrated the first current-injected light-emitting sample of GaN (Johnstone 1999; Schubert 2006). However, further development work was terminated due to device inefficiency and a consumer survey that identified a need for cheaper LEDs, rather than new colours. The initial foresight in commissioning the research in order to develop flat panel displays was superseded by a conservative attitude towards developing the device for commercial application. This is an exemplary case of the difficulties in understanding the potential impact of breakthrough technologies at the early science phase.

Over a decade later in 1989 Isamu Akasaki (of the University of Nagoya) demonstrated the first doping and conductivity of GaN(Schubert 2006), overcoming key limits of using the material as a semiconductor. The work was funded by Toyoda Gosei who were already committed to an older type of LED and thus withdrew from funding further development. The lack of funding and support for commercialisation from the initial sponsor proved to be a constraint as the breakthrough was not pursued successfully by Akasaki but instead used by rival Shuji Nakamura (of Nichia Corporation) to produce the first viable blue GaN-based LED in 1993 – the GaInN LED (Johnstone 1999; Morton and Garbriel 2004; Schubert 2006).

Nichia Corporation's pursuit of GaN LEDs was a conscious decision – the company wanted to succeed in an area not dominated by larger players who could leverage their scale and defeat smaller players such as themselves. The motivation was thus to fill a market gap (pull) with a technology to fill that gap exactly (push), much like RCA's earlier motivation. Research and development to increase efficiencies and performance prior to production scale-up was funded whole-heartedly by the Corporation. In one year alone, $3.3m was provided - a huge sum for a relatively small company experimenting with an uncertain technology. Development work succeeded in increasing performance and efficiency and the LEDs were commercialised. The path through to commercialisation was driven by Nichia Corporation's chairman's dedication to independent research. This case is an exception to what is more common - the commercialisation of breakthrough technology is known to be a risky process and fundproviders will need much more reassurance of an existing market before committing millions of dollars to development work.

Despite Nichia Corporation's commercialisation attempts in the mid-1990s, the technology is not yet mainstream. A strategic alliance was formed with Lumination LLC (a subsidiary of GE) in 2007. Lumination went on to launch the *Vio* high power white LED, which uses phosphor coatings to tint the blue light into white light. White LEDs have the potential to replace the ubiquitous light bulb and so the prospects for Nichia's latest venture are promising.

After Nakamura's first successful LED, the US government tried to counter-attack. The Advanced Projects Research Agency (Johnstone 1999) launched three research consortia involving among others; AT&T, Kodak, Xerox, Hewlett-Packard and Philips. After three years, the attempt to replicate Nakamura's work had failed and the attempt was terminated. The situation is ironic as the foundation materials advances were made in America (at the RCA Laboratories in the late 1960s) but ignored due to early judgement of whether the breakthrough science could be converted into a commercial opportunity.

Despite leaving the race for a GaN LED after Akasaki's preliminary work, Toyoda Gosei resumed work on GaN LEDs in 1995. A seven year research programme followed costing about 700million yen (approximately £4.75m) which resulted in the filing of 50 associated patents. In 2001, a joint development programme with Toshiba was announced (Toyoda Gosei 2001(Zorpette 2002). Since 2002, the technology has been highlighted in both company's annual reports demonstrating their commitment to the commercialisation attempt. Although Toyoda's reports are particularly optimistic of the opportunity to capitalise on GaN LED technology[7], it is fair to speculate that the original exit from the funding routine may have constrained the full impact of commercialisation by losing any first-mover advantages. Of course, it is easy to judge breakthrough

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[7] Reporting in 2006, for example, 16.5% of optoelectronics business unit sales being attributable to GaN LEDs

technologies with hindsight – far more useful is being able to anticipate the impact of such technologies at the point where commercialisation decisions are made.

In 2003, Sandia Laboratories(Zorpette 2002)(Sandia 2003) in the USA announced production methods to produce more durable LEDs. The driver for such technology development came from a need for more durable LEDs and a potential promise/suggestion from a government-based sponsor (see below), both encompassing a market pull. The research was part-funded by an internal three-year $6.6million Laboratory Directed Research and Development Grand Challenge grant and part-funded by the Department of Energy Office of Building Technologies. In turn, these were both funded the US government. The project was also in collaboration with Lumileds Lighting (part of Philips Solid State Lighting)(Zorpette 2002).

In 2002, Lumileds themselves launched the *Luxeon* InGaN LED, claiming it to be the best white lighting source available today. The funding and industry links afforded to Sandia placed it in a strong position to develop technology with good commercial prospects – hints/help from a government department regarding building technology requirements, legislation, etc and industrial/commercial insight from Lumileds. Again, the value of strategic collaborations is highlighted. The challenge is working out *who* to collaborate with, and then *succeeding in arranging* such a programme.

GaN-based LEDs are far from being a mainstream technology in any one field. Various research programmes have been set up across the world in order to develop winning technologies that may be commercialised. Some of these include:

- **Sandia National Laboratories:** These laboratories are undertaking ongoing research programmes using US government funds (undisclosed amount) [**34**]. The laboratories typically supply technology to the US Department of Defense with some work on civilian applications in collaboration with corporate partners such as Lumileds Lighting (as aforementioned). The collaborative links to government departments and corporate entities will help ensure research is application-focused, thus helping to deliver commercial products faster.

- **Korea Photonics Institute:** A structured 3 stage programme set up in 2001 (LEDs 2002) and driven by industry giants such as LG and Samsung as well as the Korean government. The government is committed to the cause, providing over 70% of funding with the balance split between the local authority and industry. The programme employs 70 PhD-educated staff, possesses $365million worth of equipment and has access to up to $20million of funding per year. The involvement of *smart* sponsors such as LG and Samsung will help develop the commercial focus of any research work. Furthermore, government involvement may help to create demand, particularly as GaN LEDs are known to be energy efficient light sources and could reduce the country's lighting bill and carbon footprint.
- **German Research Foundation:** This central, self-governing research funding organisation has committed to providing €11m (2008-2011) and a further €24m (2008-2020) of public research funds to a consortium of German technical universities and research institutes[8]. This is with the aim of further developing understanding and applications in GaN-based devices. An advantage of this fund is the long-term view in committing to over a decade of research from the outset. The case studies conducted in this project show breakthrough technologies undergo long periods of development prior to application – recognising this early can only help keep expectations realistic.
- **NoveLELS:** A consortium of aerospace companies, SMEs and university research groups set up in 2007 (LEDS 2003, Rapidonline 2003) with £1.7m from the UK Department for Business, Enterprise and Regulstory Reform and £1.6m from consortium partners. The scheme aims to develop GaN LED based light sources and establish the UK's position in this emerging field. The diverse range of groups involved may help innovation but there are obvious risks of bureaucracy or lack

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[8] Such as the Fraunhofer Institutes and Ferdinand-Braun-Institute

of focus due to the sheer number of people/organisations involved.

- **The Cambridge Group:** Funded by the Engineering and Physical Sciences Research Council (EPSRC) and the Department for Trade and Industry (DTI), Professor Colin Humphreys' group have devised a method to produce LEDs much more cost-effectively (RSC 2009). The result is promising from the point of view of reducing the cost of GaN LEDs (a key constraint to replacing light bulbs in everyday lighting). The group has so far collaborated with RF Micro Devices (owner of Filtronics), Qinetiq, Forga Europa and Thomas Swan (subsidiary of Aixtron AG) to develop the method into a commercial opportunity.

Figure 5: Collaboration for low-cost GaN LEDs

The future for GaN LEDs is by no means decided and the final stage of this report will explore how learning from commercialising past generations of LEDs can help exploit opportunities presented by low-cost GaN LEDs.

2. Commercialisation Patterns

In section II the commercialisation stories of three LED technologies were discussed to paint a general picture of the technology development landscape. In section III, key themes are drawn across the various LED commercialisation histories with exemplars used to illuminate the broad features observed.

2.1. The Exemplars:

Exemplars will be discussed in the first instance when indicating patterns across the case studies, with supporting ideas from alternative commercialisation paths.

Figure 6: Exemplar for traditional`LEDs

From the commercialisation history of traditional LEDs, the chain from General Electric through Monsanto to Hewlett-Packard presents an interesting story of early exits, collaborations and (US Air Force) funding enabling commercialisation.

Figure 7: Exemplar for OLEDs

From OLEDs, the chain of license agreements and collaborations leading to GE setting up large scale production provides a fruitful example of the modern, virtual corporation where expertise is drawn in from partners to enhance one's own business model/strategy.

Figure 8: Exemplar for GaN LEDs

The exemplar from GaN LEDs is rather a shorter chain than the other exemplars but represents some interesting features: early exit via Toyoda Gosei, market re-entry, (government-funded) dedicated research and collaborative efforts with Toshiba.

2.2. Themes observed:

The themes observed across the case studies are separated into subsections of lessons learned from history, obstacles prevalent in this industry, other common (external) factors and key funding typologies.

Precedence:

Prior R&D:

Holonyak's 1962 breakthrough in producing the first viable GaAsP LED was built upon prior research into the materials properties of Gallium Arsenide and Gallium Phosphide. Solution-focused research allowed Holonyak to strive for a (red) visible-light emitting device from the outset. Aiming for a practical device meant research efforts could be geared towards devising a product that could be commercialised more easily than if the research was carried out solely to find new materials properties.

Hewlett-Packard was another player in the commercialisation of GaAsP LEDs that used prior work as a springboard for developing the technology. The company had previously carried out development work to make components in their instrumentation displays solid state devices with the exception of Nixie tubes – the glow tubes that provided the numerical displays. By replacing these tubes, Hewlett-Packard could achieve electrical compatibility for devices, improving power consumption/efficiency thus creating another selling feature. LEDs were used as the replacement and the opportunity provided by previous research again aided the path to commercialisation.

In OLED technology, the partnership started in 2002 between UDC and DuPont utilised the work carried out by DuPont in developing a solution-based electronics printing process and by UDC in developing high-performance P-OLEDs. A key transition in commercialising science is the technology development phase where production processes are formed to scale the science up; DuPont's efficient and fast production techniques slashed associated production costs for OLEDs and helped support this transition. UDC's technology was licensed by Konica Minolta in 2008 who are collaborating with GE to improve the roll-to-roll printing of their lighting products. Thus, via a chain of collaborations, GE's attempts to commercialise OLED lighting products has benefited from preceding technological breakthroughs.

Unsuccessful commercialisations:

Lessons can be learnt from unsuccessful commercialisations as well as from prior R&D. Nichia Corporation actively sought new, innovative research after previous attempts to commercialise other materials such as Gallium Arsenide and Indium Phosphide were unsuccessful when larger, more powerful firms such as Sumitomo Electric trumped their efforts. Thus, pursuing GaN LEDs (when competitors were not) was derived from previous experience and, as we have seen, allowed Nichia to be the first in a new market in 1993. Had it competed with other, larger players, Nichia would arguably have never seen such success, nor so fast[9].

Obstacles:

Envisaging the value or applicability of an innovation:

By the very nature of breakthrough technologies, it is difficult to envisage future applications and the value of the innovation. In traditional LEDs, General Electric was

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[9] Growing steadily to contribute more a third of the world's total GaN LED production of 13-15 billion units in 2005 and achieve sales of $1.4billion in 2001 (Johnstone 1999)

already committed to developing silicon products and declined commercialising Holonyak's GaAsP LEDs after a failed initial attempt[10]. Upon GE's exit, Monsanto Corporation successfully developed the LEDs and went on to sell for over a decade (doubling sales volumes each year from 1968-70) (Schubert 2006). Monsanto themselves later resisted an opportunity by prematurely rejecting M George Craford's yellow LEDs. This decision relied heavily on market research that suggested consumers wanted cheaper LEDs, not more colours. In subsequent years, alternatively coloured LEDs have seen many applications ranging from traffic lights to billboards and Monsanto's rejection presented an obstacle to commercialising the new LEDs sooner. Premature rejection of GaN LEDs occurred in the early 1990s when Toyoda Gosei did not move immediately to commercialise Akasaki's developments in GaN. Toyoda was committed to developing an older form of LED, the MIS LED. The firm later entered the race to commercialise GaN LEDs in 1995 – the early rejection being proven as a poor decision as Toyoda Gosei lost time and IP to its main competitor Nichia, who moved first.

Competing against substitute technologies:

The presence of substitute technologies, namely LCD, has presented a recurring obstacle for various generations of LED. With traditional LEDs, market erosion occurred due to LCDs in the late 1970s and 1980s[11] causing intense price competition between incumbents in the LED market and the eventual exit of players such as Monsanto Corporation and Texas Instruments. In 2007, when Sony launched their first OLED television, the selling price of approximately $1740; LCD televisions of comparable size cost less than half the price, were still new to the market and offered superior performance too (compared to older cathode-ray tube televisions). Sony's offering captured negligible market share and at least part of this failure can be attributable to

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[10] Arbitrarily pricing the devices at $260 and selling via an amateur radio fanatics catalogue (Schubert 2006).

[11] Plunging 40% in 1977 to $50m (Johnstone 1999)

the presence of a substitute technology that offered *enough* benefits over prior technology, at a lower price.

Commonalities:

Legislation:

Legislation in the USA in 1985 for Centre High-Mounted Stop Lights on cars created a large market for traditional LEDs. Stanley Electric, via collaborative work with General Motors, developed LEDs that would fit the application and the LEDs were first applied to the Corvette and then the 1993 Cadillac. Being able to respond to legislation is important, particularly in the mass automotive market where deals with car makers correlate to tens or hundreds of thousands of sales. The creation of markets by legislation and regulatory changes are thus external factors worth watching.

Location:

Being positioned in a country that is pursuing a particular technology is also beneficial. In order to capitalise on the emerging field of OLEDs, both Germany and Japan have consciously set up research and support programmes to develop technology, namely OLEDFAB and the Japanese Research Institute for Organic Electronics respectively. OLEDFAB was initiated in 2003 to start a pilot production plant to enable research and production scale-up. The Japanese scheme (started in 2008) is intended to help with further industrialisation and commercialisation of OLEDs. Being positioned amongst such a national drive means technology developers and firms trying to commercialise will be able to pool and use each others' resources. The positive stance towards a particular type of innovation is also beneficial as it shows a commitment from governmental organisations in funding further R&D. Another example of national intent may be found in the commercialisation history of GaN LEDs. As a counter-attack to Nichia Corporation's production of GaN-based LEDs in 1996, the USA's Advanced Projects Research Agency launched three consortia to replicate the work. Despite involving the likes of Xerox, Hewlett-Packard and Philips, the attempt was unsuccessful.

A lesson may be learnt here – national support needs to pre-empt and drive a technological breakthrough into commercialisation, rather than follow for the sake of competing.

Societal trends:

Today's society is increasingly aware of energy efficiency. This is driven by two factors: rising energy prices as well as the need to reduce carbon emissions. LEDs of all varieties present opportunities for more energy-efficient devices than traditional light sources. This societal trend is an excellent opportunity for focused product development and marketing. An example of this is GE's *ecomagination* - a cross-departmental scheme for environmentally-focused products. In GE Lighting, GaN LEDs form an integral part of this initiative and the firm is only too happy to appeal to society's need for energy efficient products via its annual reports and press releases.

Funding typologies:

In the commercialisation of traditional LEDs, two types of funding played the heaviest roles: military and corporate funding.

Military funding:

In post-war America, government research and development spending was dominated by military spending to provide products for defence applications. Holonyak's production of the first GaAsP LED was funded by the US Air Force which allowed the commercialisation process to continue instead of the venture dying with GE's withdrawal. Via this sponsorship, Holonyak was free to discuss his work with other companies, thus allowing materials discussions with Monsanto Corporation. Monsanto integrated vertically from their chemicals base into electronic devices.

In the UK, parallel research on Gallium Phosphide LEDs was occurring at Services Electronic Research Laboratory, part of the Royal Naval Scientific Service. Initially, products were initially kept for sale to the military but in 1966 were made available for general sale via Ferranti plc who subsequently developed the devices further to increase efficiency. In both the American and British case, the role of military funding is immense; firstly, providing much-needed funding in the early science phase and, moreover, keeping a product-focused approach which meant research was geared towards a guaranteed market from the outset.

Corporate funding:

The discussions allowed between Monsanto and Holonyak (permitted under the Air Force grant) lead to further commercialisation opportunities when Bill Hewlett (CEO of Hewlett-Packard) committed H-P's resources to developing the technology. Despite the company's own marketing department doubting the viability of replacing light bulbs, Hewlett pushed forward with the venture as he considered hand-held calculators to be a better, future application opportunity for LEDs. The gamble was right – calculators with LEDs became widespread and Hewlett-Packard sold 100,000 (despite a high selling price of $395) in the first year (1971) and over 15 million units between 1971-1994 (Johnstone 1999). Thus, the role of the corporation in being able to fund changes in direction and new applications is important. The risk associated with finding and capitalising on unimaginable opportunities can be better absorbed by a large corporation than a start-up or SME.

Collaborations and licensing:

The arrangements between exemplars commercialising OLEDs are a good commentary of modern routes to applying science. Collaborations between GE/Konica Minolta as well as between DuPont/Universal Display Corporation were linked via a licensing agreement between Konica Minolta and UDC to use UDC's technologies. In an era of globalisation, optimised supply chains, core competences and lean operations, firms tend to focus on one area of the value chain and pull in resource, expertise and IP from partners. Such trends are prevalent in both SMOLED and P-OLED commercialisations with Kodak, CDT and Plastic Logic licensing their IP out. Arguably, start-ups and SMEs have more chance of making some use of their innovation than in the days where the conglomerate ruled every industry. However, the same financial issues arise when first moving research out of the laboratory into the commercial sphere - being able to protect technology via patents, to monitor and enforce licenses, to market products, etc all require funding to be able to launch into arrangements with partners. Business models for breakthrough technologies may be evolving but funding remains a pivot point in successful commercialisations.

Government funding of early science:

In 1995, after originally exiting the race to commercialise GaN LEDs, Toyoda Gosei re-entered development by embarking on a 7 year research programme part-funded by the Japanese Science and Technology Corporation (approximately £3.7m) with the balance from within Toyoda. The programme was given approximately £4.75m in total and generated 50 associated patents. In America, Sandia Laboratories received internal funding of $6.6m over 3 years from the Laboratory Directed Research and Development Grand Challenge and external funding from the Department of Energy Office of Building Technologies (undisclosed amount). In the UK, the NoveLELS project commenced in 2007 to develop GaN LED-based sources and establish a UK capability in the field. The project received a total of £3.3m from the Department for Business, Enterprise and Regulatory Reform (£1.7m) and consortium partners (£1.6m). Alongside this, Professor Colin Humphreys' Materials Science group at the University of Cambridge received various rounds of funding (the largest being £1.5m) from the EPSRC and the DTI to improve production of LEDs. The group is collaborating with a variety of companies to try to commercialise the developments which will mean a 90% reduction of production costs. Although there are many big players in the GaN LED markets, there appears to be a role for government departments and funding councils in helping to fund and inform commercialisation efforts. To be able to exploit such opportunities, those involved in early-stage science need to understand how to interact with government departments/ funds and how best to use them to the advantage of commercialisation attempts.

3. Informing the Commercialisation of Low-Cost GaN LEDs

3.1. Background on the early science research group:

Professor Colin Humphreys' Gallium Nitride group at the materials Science and Metallurgy Department (University of Cambridge) present a promising hope in commercialising GaN LEDs. The group have been developing techniques to produce an LED with all of the benefits of GaN but at a far cheaper price than is currently available on the market. Although still in the early science phase, the case presents an interesting example of research that has been commercially focused from the outset.

The group has received various rounds of funding from the EPSRC (totalling £5.4million) and the DTI (£1.5m) and is collaborating with industrial partners in order to produce a commercially viable product. Once the Cambridge Group have improved the basic science, QinetiQ will reproduce wafers on a multi-wafer platform, ready for Filtronic to convert into electronic devices. Forge Europa will play an advisory role throughout the collaboration.

Figure 9: Collaboration for low-cost GaN LEDs

3.2. The collaborators

Forge Europa Ltd is an independent SME based in Cumbria. With an asset base of less than £100,000, the firm is the collaborator with the least financial clout. Forge Europa play an advisory role, utilising their expertise in designing and developing LED-based products.

Thomas Swan Scientific Equipment (TSSE) Ltd is a subsidiary of Aixtron AG[12], a German company providing deposition equipment to the semiconductor industry. TSSE is based near Cambridge and reported turnovers of £20-£40million prior to takeover by Aixtron. Aixtron is reported to lead the field in semiconductor equipment with a 70% world market share in the machinery needed to mass produce LED devices.

QinetiQ plc was formed in 2001 from the UK Government's Defence Evaluation and Research Agency[13] and is a leading supplier of technology to the Ministry of Defence. The technology company commonly reports turnovers over £1billion and has a world reputation for being at the cutting edge of research. The company's research centre in Malvern is reputed internationally for capabilities in growing GaN-based structures for transmitters. Thus, it has equipment and expertise vital in advancing this collaboration.

Acquired in 2008 by American firm RF Micro Devices Inc[14], Filtronic plc[15] is based in West Yorkshire and designs and manufactures microwave products and compound semiconductor devices. RF Micro Devices is a leading global player in the design and manufacture of semiconductor devices and reported the acquisition of Filtronics as expanding its asset in GaAs manufacture. It remains to be seen whether this acquisition will affect the plans to scale-up GaN LED production post-technology development by the Cambridge group.

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[12] Achieved revenues of over 200million Euros in 2007 and 2008

[13] Itself formed in 1995 by combination of the Defence Research Agency, the Defence Test and Evaluation Organisation, the Centre for Defence Analysis and the Protection and Life Sciences Division

[14] Revenues of approximately $1billion in both 2007 and 2008

[15] Revenues of £54.6m and £38.4m in 2008 and 2007, respectively

3.3. From Current Stage to Commercialisation:

Technology:

In recent years the group have managed to make ongoing breakthroughs in GaN device efficiencies and production methods/yields.

The growth of GaN on a 6” Silicon substrate rather than 2” Sapphire wafers is a particular breakthrough that means production costs can be reduced to 10% of previous offerings. This cost saving is attributable to Silicon being available/fairly easy to grow in 6” wafers whereas other candidate materials are only available in up to 4” diameters. Being able to produce on larger wafers means order of magnitude increases in the volume of diodes made at once, thus helping achieve economies of scale in production.

A common criticism of past GaN LED offerings is the short lifetime and sudden failures associated with the devices. Another key finding by the research group is isolating the cause of premature failure to packaging, rather than being intrinsic to the devices themselves. The advances achieved by the group mean low-cost GaN LEDs are close to causing mass disruption in the marketplace. There are, however, a few more obstacles to overcome.

The packaging issues that result in premature failures need to be addressed. Furthermore, the output of the LEDs tends to be inconsistent leading to drifting colours. This issue needs to be resolved for GaN LEDs to be accepted as reliable devices for the future.

Phosphors can be used to tint blue light emitted from the LEDs into white light, which has many more applications. Research into novel phosphors has commenced in order to improve the colour rendering of this light, offering more natural and acceptable tones. For the highest quality white light e.g. that is used for inspection and reading, red, green and blue LEDs are mixed to emit white light. Currently, the limit to efficiency here is due to the green emission. Thus, work needs to be completed to optimise the efficiencies of this highest quality light.

To bring from research into prototype devices and products, low-cost GaN LEDs require improvements in the areas identified. Beyond this, the technology will be ready for scaling up by QinetiQ and Filtronic.

Market:

GaN LEDs are currently used in some applications in both lighting and display.

Lighting	Display
Traffic lights (China, Singapore, California), Backlights for mobile phones, Interior lighting for cars/buses/planes, Torches, Car headlights (e.g. Audi A6 or A8), Streetlights, Airport runways, Traffic signs on motorways, Front bicycle lights	Large full-colour displays e.g. advertising billboards and displays such as in Times Square, New York or Piccadilly Circus, London

Figure 10: Current applications for GaN LEDs

By making GaN LEDs into a low-cost white light source, the key aim of the programme is to penetrate the market for everyday home and office lighting which is worth approximately $12 billion worldwide (Zorpette 2002).

Furthermore, research has identified the potential for GaN LEDs to be adapted to emit light in the deep ultraviolet range. Bacteria have no coping mechanism against UV light thus providing a method to purify water in the developing world. It is claimed that half of the hospital beds around the world are occupied by dirty water-related illnesses, making this a more prevalent cause of suffering in the developing world than AIDS. Thus, the development of GaN LEDs into a low-cost device can help in much-needed water purification.

GaN is a particularly robust material. From an understanding of the basic materials properties, I would suggest GaN LEDs could be applied in areas such as military and sensing devices where contact and harsh physical conditions exist. Here, there is great need for high performance devices but with low cost sensitivity, thus giving a platform from which GaN LED technology could be further developed and perfected. It remains to be seen whether the involvement of QinetiQ will lead to such market opportunities.

Funding:

So far, the Cambridge group have received funding of £5.4m since 2000 in various rounds from the EPSRC for research directly related to the development of GaN LEDs. In addition, the collaboration with Filtronic, QinetiQ, TSSE and Forge Europa was granted £1.5million in 2007 from the DTI (matched by £1.5m of funding from the commercial partners). TSSE donated deposition equipment with a list price of £500,000 in 2000. Although this last item is not funding in the strictest sense, the provision of industry leading equipment is a key facilitator in allowing the group to enhance their production-focused research activities and build a prototype, thus being able to demonstrate the viability of the device.

Although the programme is progressing towards to scaling-up production there are still some obstacles to overcome if market penetration is to be achieved (see above). Thus, further R&D will be required to overcome these difficulties and any which arise out of current research. The non-linear development path of early science makes it difficult to predict how exactly applications will be developed, and how much more funding may be required but the identification of several areas for improvement suggests it is to the order of millions.

If and when low-cost GaN LEDs are commercialised, the technology has the potential to revolutionise the marketplace. Intellectual property needs to be protected in order to prevent competitors and market entrants capitalising on the collaboration's efforts. In particular, the Cambridge group will need financial support in this area as, unlike its industrial partners, the group will have limited resource to defend its interests against market incumbents such as Toyoda Gosei.

In order to raise much-needed funds in the future, there are various avenues that may be explored. In the first instance, further government support such as from the EPSRC may be tapped again to provide necessary funding. However, the funding on offer is, of course, finite and may cease as the work nears prototyping. Government grants are typically provided at early stages of commercialisation between when finances from family and friends are exhausted but before the venture is developed enough to achieve venture capital or business angel funding.

Licensing the technology is another possible route to help fund further research. However, it is unlikely to prevail as the group is tied to collaborators who wish to scale production up when the technology has evolved. Sharing all-important IP usage and development rights to potential competitors is an unattractive proposition for the Cambridge group's industrial partners. Furthermore, the group will lack the expertise to arrange and uphold a licensing business model and, arguably, this would dilute time and effort that should be spent developing the technology.

At the next phase of development, once more obstacles to low-cost production have been removed, it is feasible that funding may become available via the collaborators. RF Micro Devices are perhaps the most inclined to sponsor due to already owning fabrication equipment that could produce the low-cost GaN LEDs. Thus, the smooth transition to mass production would present an excellent opportunity for Filtronic's owner to enhance its product portfolio.

Funding from other corporate sponsors is also a possibility – particularly as the technology moves even closer to full production. It is very likely that such a sponsor may come from abroad- particularly South East Asia where new electronics technology is commonly piloted or the USA which is traditionally a frontrunner in entrepreneurial activities. This would be somewhat of a disappointment from the perspective of the UK government which has consistently supported the project via the EPSRC and DTI.

Another source of finance may be military funding. As aforementioned, the robust nature of GaN lends itself to high performance applications such as would be expected in military devices. QinetiQ's involvement in the scheme at the collaboration phase offers credibility to the venture and, speculatively speaking, there may have even been a conscious effort by the MoD to engage in the work from the outset. Examples of the benefits of military funding have been exemplified in previous LED technology commercialisations (SERL with GaP LEDs and the US Air Force with GaAsP LEDs). The development of niché applications prior to penetrating the mainstream lighting market was predicted by market research firm Strategy Analytics in 2007 [**32**]. Thus, the drive of military product-focused research and funding may play a part in helping to commercialise low-cost GaN LEDs.

Military funding may be part of a wider opportunity provided by government in the form of public procurement. Public procurement could mean an early market in military applications and then wider applications in home and office lighting. The energy efficiency inferred by GaN LEDs lends itself well to promotion by government building regulations, for example. In this way, a market for the devices would be guaranteed and be a chance for government to follow-up on early-stage grants, e.g. from the EPSRC, helping in the final drive for commercialisation.

Key players:

From the perspective of the Cambridge group, most of its industrial partners are strong key players at this juncture. RF Micro Devices, QinetiQ and Aixtron understand the group's history and hold/will hold vital positions in the effort to commercialise with access to much-needed expertise, equipment and finances.

Another highly influential group are governments due to their ability to create market opportunities. In March 2007, the UK planned to phase out light bulbs by 2011. The EC and California announced similar intentions to be achieved by 2012 and the rest of the USA by 2014. Australia, Brazil and Switzerland have already completed the task. By eliminating the market for the ubiquitous light bulb, such governments have created wide opportunities for any economical and high-efficiency light source.

The G8 governments amongst others are all investing in programmes to develop alternative sources for illumination. The prevalence of funding and opportunities in the field is both an advantage and disadvantage. Whilst direct (e.g. other GaN LED producers) and indirect (e.g. other lighting device producers) competitors will be borne out of such programmes, the industry and individual researchers/research groups may benefit from many parallel programmes. Alternative programmes will investigate a variety of techniques and ideas, eliminating weaker options and wasting their resources. Thus, the Cambridge group may be fortunate enough to capitalise on the work of others. Thus, it is important for the Cambridge group to be aware of developments elsewhere, so as not to be left behind by any faster progressing programmes.

A further argument is that if these governments are encouraging alternative illumination programmes, they will be familiar with the attributes of successful devices and thus may be more receptive to a superior offering – the low-cost GaN LED. The potential for public procurement policy to play a significant role is highlighted once again. By the acceptance of technological innovation and the creation of relevant market opportunities, governments can sway the entire path to success for breakthrough technologies.

Apart from the EPSRC and DTI funding for the Cambridge research group's work, the UK has also sponsored the NoveLELs project. Here, a vertically integrated consortium of university research groups, aerospace companies and lighting device companies received £1.7million from the government's Department for Business, Enterprise and Regulatory Reform in order to develop GaN-based LED sources and establish a UK capability in the field. The programme focuses on producing LEDs for backlighting LCD displays or niche aerospace applications, rather than general illumination – the primary focus of the Cambridge group's research. Another contrast is that the programme does not intend to delve into mass production and is restricted to early development rather than full commercialisation. Some commonalities with the Cambridge research group, however, are that both groups are investigating advanced phosphors and efficient packaging. Discussions in these key areas may help the Cambridge research group to overcome the last obstacles preventing commercialisation.

4. Concluding Remarks

Key lessons have been learned by studying the commercialisation histories of traditional LEDs, Organic LEDs and GaN LEDs. Recurring issues in commercialising these technologies have been identified with a view to informing the commercialisation of the Cambridge research group's low-cost GaN LEDs. In this section, we draw these ideas together and link to the wider work of the CIKC.

The case study approach has the benefit of hindsight. When commercialising a breakthrough technology, it is difficult to say (with certainty) which of the many possible paths for development is best. The lessons learned from past commercialisations provide some insight on choosing methods to capitalise on science but it is worth noting that there is a danger of oversimplifying the process. Historical commercialisations are a guide on how to progress, rather than a panacea – each breakthrough technology is unique and needs to be treated as such to make best use of the innovation.

4.1. Lessons Learned

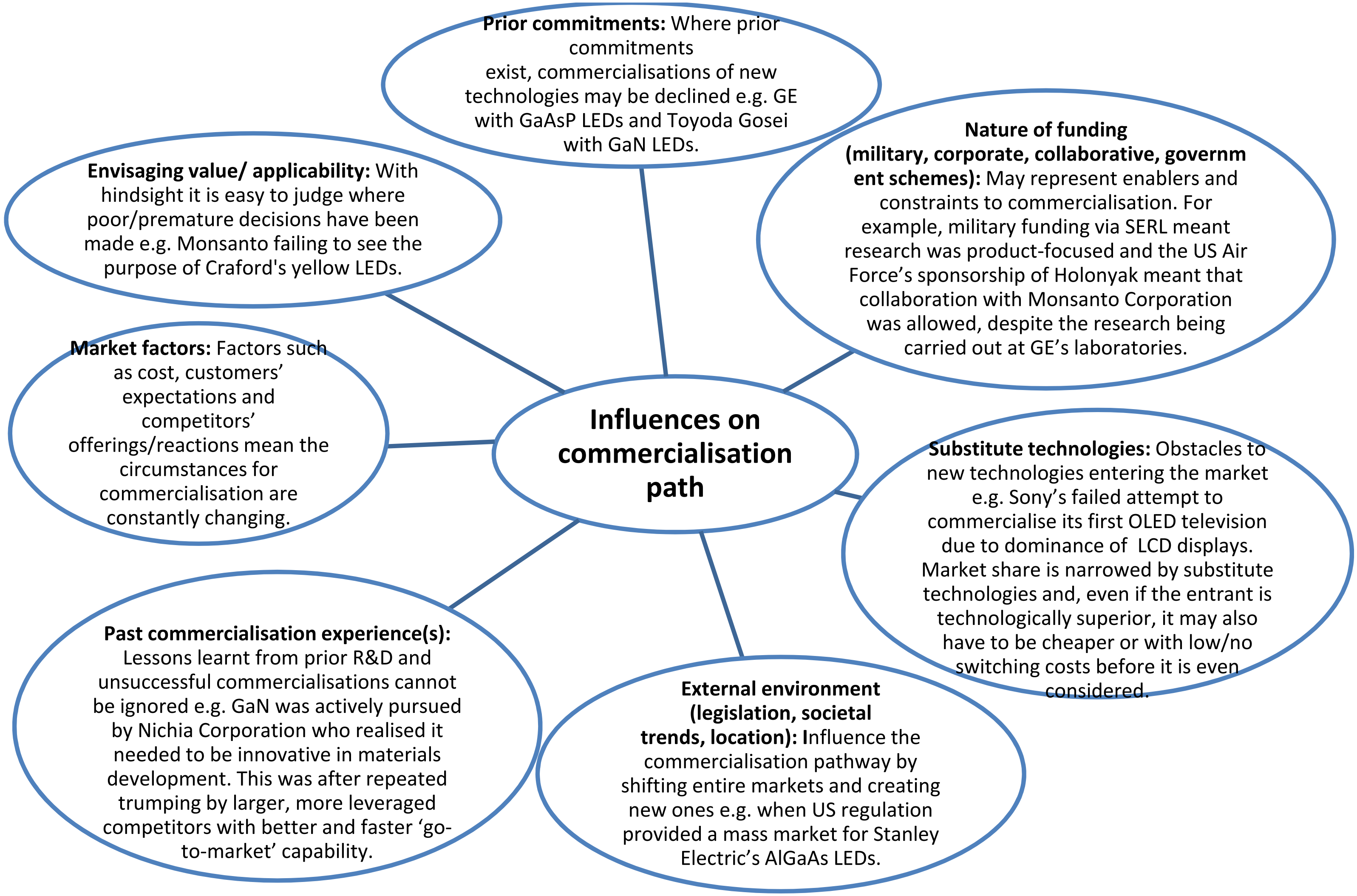
Past experiences of prior science and unsuccessful commercialisations have helped to gear science successfully towards commercial opportunities, rather than failed attempts to develop technology. Furthermore, the external environment has been shown to bear great weight on commercialisation success; government regulation, research programmes and societal trends all have dramatic effects on the viability of technologies breaking into the marketplace.

Obstacles prevalent in this area of technology have been indicated with key sticking points shown to occur time and time again. Being able to imagine the applicability of breakthrough technology is a vital issue; arguably, the commercialisation effort of GaN LEDs is positioned to do well by having various future market applications in mind and gearing effort towards these.

Funding is a vital aspect in being able to capitalise on science. In order to commercialise low-cost GaN LEDs, past LED generations have indicated government and corporate funding (particularly from collaborators) as possible and likely funds for further exploration.

The key players in the attempt to commercialise GaN LEDs have been identified, both those so far and those looking forward. Collaborative partners have a strong role to play in bringing the technology forward but perhaps the most influential will be government(s) and their ability to create markets for low-cost, high-efficiency lighting.

Commercialisation paths of the technologies studied were found to be non-linear and prone to many influencing factors such as those detailed in figure 16.



Influences on commercialisation path

Prior commitments: Where prior commitments exist, commercialisations of new technologies may be declined e.g. GE with GaAsP LEDs and Toyoda Gosei with GaN LEDs.

Nature of funding (military, corporate, collaborative, government schemes): May represent enablers and constraints to commercialisation. For example, military funding via SERL meant research was product-focused and the US Air Force's sponsorship of Holonyak meant that collaboration with Monsanto Corporation was allowed, despite the research being carried out at GE's laboratories.

Envisaging value/ applicability: With hindsight it is easy to judge where poor/premature decisions have been made e.g. Monsanto failing to see the purpose of Craford's yellow LEDs.

Market factors: Factors such as cost, customers' expectations and competitors' offerings/reactions mean the circumstances for commercialisation are constantly changing.

Substitute technologies: Obstacles to new technologies entering the market e.g. Sony's failed attempt to commercialise its first OLED television due to dominance of LCD displays. Market share is narrowed by substitute technologies and, even if the entrant is technologically superior, it may also have to be cheaper or with low/no switching costs before it is even considered.

Past commercialisation experience(s): Lessons learnt from prior R&D and unsuccessful commercialisations cannot be ignored e.g. GaN was actively pursued by Nichia Corporation who realised it needed to be innovative in materials development. This was after repeated trumping by larger, more leveraged competitors with better and faster 'go-to-market' capability.

External environment (legislation, societal trends, location): Influence the commercialisation pathway by shifting entire markets and creating new ones e.g. when US regulation provided a mass market for Stanley Electric's AlGaAs LEDs.

Figure 11: Factors influencing commercialisation pathways

4.2. Commercialising Low-Cost GaN LEDs

Section 4 studied the current stage of low-cost GaN LEDs and proposed the developments needed to achieve full commercialisation.

Technology	•Key areas for technology improvement are identified: packaging to improve lifetime, novel phosphors to improve colour rendering and higher efficiency green LEDs for the highest quality white light.
Markets	•Further market opportunities such as everyday home/office lighting, water purification and military/sensing applications are proposed.
Funding	•Future funding is vital to progress with the most likely/worthwhile sources being collaborators and military or public procurement.
Key players	•Key players are linked to the likely funds - collaborators, governments creating markets and parallel government-backed research schemes.

Figure 12: Summary of the progress needed to take low-cost GaN LEDs from current stage to commercialisation

4.3. Informing the Work of the CIKC

With particular reference to informing government and the entrepreneurial community, the EPSRC and DTI funds have proven very worthwhile in progressing GaN LEDs during the research phase. However, research is not enough – the UK needs to capitalise on commercialisation opportunities if it is to reap the rewards of its efforts.

Funds such as those from the EPSRC and DTI allow research to occur in cases where laboratories require extra assistance outside of their own means. Exploratory work such as this is beneficial as it provides a filter for worthwhile science and unsuccessful ideas. Thus, by the end of the research phase, the potential of the science to break into the marketplace may be inferred to some extent. As the research on GaN LEDs has shown, technologies coming to the end of the research phase can not always be certain of where/how the commercialisation opportunity may be generated. The role of government has been identified as key to creating this opportunity. Public procurement can help technologies to gain market foothold, particularly in areas such as GaN LEDs where the offering has widespread environmental, technological and cost benefits. A linked-up industrial policy encompassing early science funding and empowering government departments to make use of and create markets for the research will help the UK to take advantage of this technology.

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Appendices

Post-war Innovation Funding in the USA

After World War II, the American government was heavily in support of R&D, with industrial policy being centred on the belief that basic research was the ultimate source of economic growth. Between 1945 and 1969, the USA's resource allocation to R&D was worth $25.6 billion; over twice the combined spend by West Germany, France, Japan and the UK ($11.6 billion).

The National Research Foundation was set up in America with the intention of supporting research in universities but post-war politics meant various agencies secured the bulk of R&D funding, rather than this single civilian agency. By the end of 1950, 90% of R&D spending was controlled by the Defence department and the Atomic Energy Agency.

The role of defence spending within the semiconductor industry is highlighted in Figure 13: Domination of US Defence spending in semiconductor production. It is worth noting that between one-quarter and one-half of semiconductor production was for defence applications every year. Any study of the development of devices in the post-war era must consider the might of military applications in this area of technology.

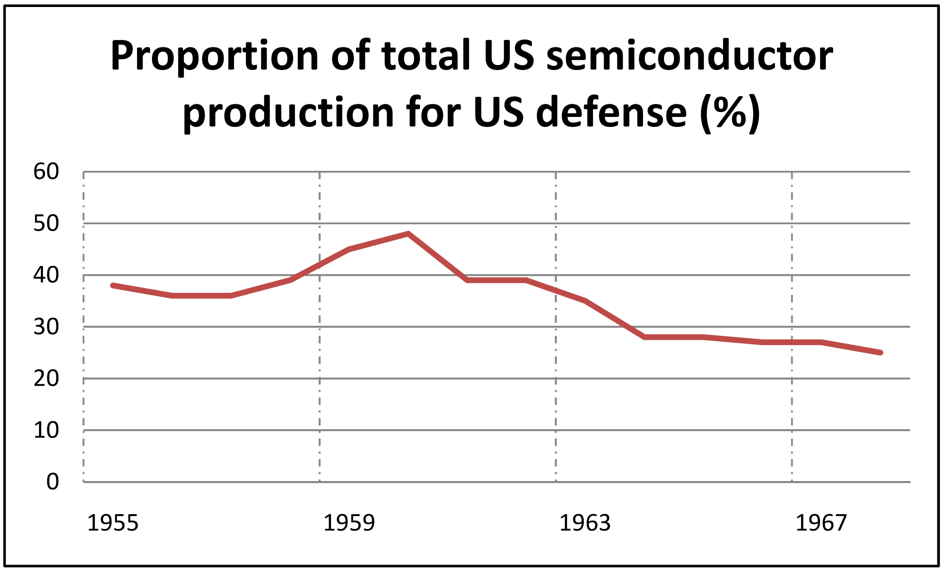

Figure 13: Domination of US Defence spending in semiconductor production

EPSRC Funding of the Cambridge Group

Date	Title	Fund (£)
Jan 2000 – Oct 2003	The development of improved MOCVD growth techniques for gallium nitride layers and device heterostructures	892 508
Feb 2003 – Apr 2003	Exploratory proposal to grow and characterize gallium nitride on silicon	53 664
May 2003 – Jun 2003	Next generation of GaN-based materials	1 217 962
Oct 2003 – Jul 2007	Gallium nitrite LEDS for display applications	375 222
Nov 2006 – Sep 2010	Materials challenges in GaN-based light emitting structures	1 362 143
Mar 2009 – Feb 2012	Science bridge award USA – Harnessing materials for energy	1 480 152