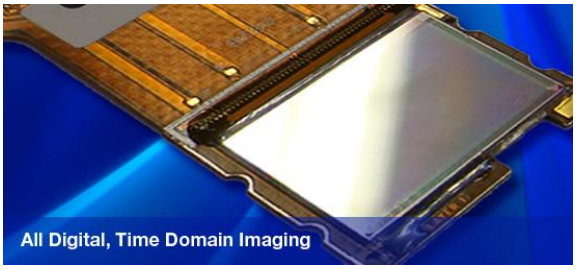
Institution: PHYESTA

Unit of Assessment: UoA 9 – Physics

Title of case study: Commercialisation of Ferroelectric Liquid Crystal over Silicon Microdisplays

1. Summary of the impact



Impact: Economic gains
PHYESTA research has led to the setting up of a company now known as ForthDD. Since 2008 it has increased its annual revenue by more than 25% to around US $5M, and its global workforce from 25 to 35. It has released new products directly underpinned by PHYESTA research as recently as October 2012.

Significance:
A consortium involving PHYESTA staff in collaboration with Edinburgh's School of Engineering and five industrial partners realised the world's first high-resolution ferroelectric liquid crystal over silicon (FLCOS) microdisplay. This digital display attracted investment from the UK, Taiwan, and USA of over $40m, and was taken forward to production by MicroPix, MicroVue, and Forth Dimension Displays.

Reach:
ForthDD now has offices in Valencia, USA, and Berlin, Germany. The company designs, develops and manufactures single chip microdisplays used in the demanding near to eye (NTE) training and simulation systems, HD video camera viewfinders, medical imaging systems and virtual reality and head-mounted displays.

Beneficiaries:
ForthDD, its customers and business partners (e.g. in the medical imaging sector).

Attribution: This work was led within PHYESTA by Professor David Vass involving PHYESTA and done in collaboration with Edinburgh's School of Engineering.

2. Underpinning research

The Applied Optics Group at the University of Edinburgh was a cross-departmental research unit involving the Schools of Physics (now PHYESTA) and Engineering (now ERPE – the Edinburgh Research Partnership in Engineering). The Group operated under the direction of Professor David Vass (PHYESTA), who was working on liquid crystal over silicon (LCOS) devices with initial interest in their use for optical correlators, beam steerers, and beam shapers. The ferroelectric class of liquid crystals offered response times an order of magnitude faster than nematic crystals, and could be operated in a binary mode suited to driving digital applications. However, ferroelectric liquid crystal devices posed severe design and manufacturing challenges, as the thickness of the required cell was much thinner than conventional nematic liquid crystal based devices. Typically a sub-micron thickness is required and flatness, cell parallelism and uniformity are also needed to make these devices viable. At first commercial manufacturers of silicon wafers regarded such tight tolerances as unattainable using conventional processing and polishing methods. Vass, Hossack (PHYESTA) and collaborators in the School of Engineering developed designs, pulsed illumination methods, polishing techniques and silicon planarization (removal of excess curvature that can reduce optical coherence and lead to colour artefacts), which produced cells of excellent flatness and high reflectivity sufficient for coherent optical applications [R1, R2]. This work was undertaken with a SERC SCIOS rolling grant, SERC/DTI Link grant SASLM and EU ESPRIT grant HICPOBS over the period 1993-1995 for which Vass was Principal Investigator.

Further refinements in the device design led to the realisation of smart pixel structures including light blocking layers and robust backplane electronics enabling a fast digital FLCOS Spatial Light Modulator [R3], which was able to operate under intense illumination. This led to applications in routers for telecoms, holographic projectors, and optical tweezers. The smart algorithms, binary phase holograms, and fast device operation were critical in realising real time full speed operation in these application areas. The realisation of the FLCOS based holographic optical tweezers, permitted for the first time multiple trapping and real-time capture of freely moving microbes, as described in a well cited paper [R4].

While more generally applicable these advances directly addressed requirements of the emerging technology of microdisplays, which demanded improved manufacturing methods to enhance image quality and colour fidelity above threshold levels for a practical display. To the basic spatial light modulator device we added fast image processing algorithms in collaboration with GEC, STC, Admit Design, and Davin Optronics, thereby producing the world's first high resolution, video speed, full colour FLCOS digital microdisplay. This device was first showcased at the 6th International Conference on Ferroelectric Devices hosted by ENST and subsequently published in the leading journal for ferroelectric technology [R5,R6]. This prototype device was a key development bringing together VLSI design, surface planarisation, light blocking layers, fast electronic interface and ferroelectric liquid crystals in a fully operational FLCOS device. This work was undertaken over the period 1995-1998.

Personnel:
The key PHYESTA researchers involved were Professor David Vass (1993-2004; category A in 2001 RAE return), Dr Will Hossack (Academic staff, 1993-present), Professor Jason Crain (1993-present) and Dr Jochen Arlt (Senior PDRA and COSMIC laboratory manager).

3. References to the research

The quality of the underpinning research is best illustrated by R1, R2 and R3. *[Number of citations]*

[R1]	A. O'Hara, J.R. Hannah, D.C. Burns, I. Underwood , D.G. Vass, R.J. Holwill, *'Mirror quality and efficiency improvements of reflective spatial light modulators by use of dielectric coatings and chemical-mechanical polishing'*, Applied Optics, **32**, p. 5549, (1993), DOI: 10.1364/AO.32.005549, URL: tinyurl.com/mhydpes, *[14]*
[R2]	I. Underwood, D.G.Vass, A. O'Hara, et al., *'Improving the performance of liquid crystal-over-silicon spatial light modulators – issues and achievements'*, Applied Optics, **33**, p. 2768, (1994), DOI: 10.1364/AO.33.002768, URL: tinyurl.com/n7tpurb, *[18]*
[R3]	D. Burns, J. Gourlay, A. O'Hara, I. Underwood, D.G.Vass, *'A 256x256 SRAM-XOR pixel ferroelectric liquid crystal over silicon spatial light modulator'*, Optics Communications, **119**, p. 623, (1995), DOI: 10.1016/0030-4018(95)00414-4, URL: tinyurl.com/knsfftm, *[11]*
[R4]	W.J. Hossack, E. Theofanidou, J. Crain, K. Heggarty, M. Birch, *'High-speed holographic optical tweezers using a ferroelectric liquid crystal microdisplay'*, Optics Express, **11**, p.2053, (2003), DOI: 10.1364/OE.11.002053, URL: tinyurl.com/llgftlt, *[58]*
[R5]	I.D. Rankin, I. Underwood, D.G. Vass, and M.R. Worboys, *'Full colour miniature display'*, Proc SPIE on "Liquid Crystal Materials, Devices and Applications", **2651**, p.16, (1996), DOI: 10.1117/12.235358, URL: tinyurl.com/mclqaef, *[1]*
[R6]	D. Vass et al., *'A high resolution full colour head mounted ferroelectric liquid crystal-over-silicon display'*, Ferroelectrics, **213**, p.209 - 218, (1998), DOI: 10.1080/00150199808016486, URL: tinyurl.com/mpsn54d

4. Details of the impact

The Applied Optics group formed a consortium with Thorn, GEC, BNR, Davin Optronics, STC, and ENST, to perform research and development of FLCOS devices with DTI funding. The local Scottish company, ADMIT Design, used the FLCOS demonstrator to attract interest and investment. ADMIT was then bought by Central Research Laboratories of Thorn EMI, forming MicroPix Technologies Ltd in 1998. They developed the FLCOS microdisplay technology into a commercial product. Subsequently in 1995, in a joint venture with PicVue Electronics a pilot production company, Microvue, was created in Scotland, and an investment of £20m was raised to build a volume production plant in Taiwan.

ForthDD [S1], is the successor company of MicroPix and MicroVue, founded in 2005, and based in Dalgety Bay, Fife. They succeeded in bringing the technology to production demonstrating that FLCOS microdisplays could be made to adequate standard in wafer scale production. Since its formation, and over the period of the REF impact window, it has raised in excess of US $33M in investment including the 2011 injection of US $14M by the leading US microdisplay company, Kopin Corporation [S2]. ForthDD designs, develops and manufactures single chip micro-displays used in the most demanding segments of markets such as training and simulation systems, HD video camera viewfinders, medical imaging systems and virtual-reality and head-mounted displays. Entirely digital, providing 24-bit full colour images, and capable of handling high-speed motion with no visible artefacts, Forth DD's single chip imagers are especially well-matched to the new solid state LED and laser diode light sources and provide very high native resolution. In late 2012, ForthDD reaffirmed its position as the world's leading supplier of advanced microdisplays when it released the world's highest resolution full colour microdisplay. ForthDD employs over 35 staff, many in posts requiring undergraduate and post-graduate qualifications. It has annual revenues in excess of £3M, with exports accounting for 95% of its sales. *"A key selling point for Forth Dimension Displays is our ability to produce high quality images in applications where competing technologies do not quite make the grade. Underpinning this image quality are product features enabled by technical specifications such as high pixel aperture ratio and accurate liquid crystal alignment, that were first established through the PHYESTA research on backplane surface quality improvement. The backplane surface quality improvement techniques described by the PHYESTA research have been adopted by CMOS foundries, such as those from which ForthDD obtains the substrates for its current product range."* Director of Product Design, ForthDD [F1].

The improvements particularly in surface planarity and pixel fill factor achieved by PHYESTA researchers were critical enablers in FLCoS microdisplay technology, allowing them to exceed the threshold of image quality necessary to satisfy customers. The underlying manufacturing processes were made available to ForthDD's commercial CMOS foundry supplier, through publication and direct transfer, and thus were incorporated into product manufacture. The CMOS foundry has continued to refine these. Thus the manufacturability, image quality and optical efficiency of the current product range and the newly released product range rely upon PHYESTA's underlying research into manufacturing techniques. Improvements in active device surface planarity and pixel filling factors achieved by PHYESTA and collaborators were key translational steps. With the exception of the liquid crystal materials themselves and aspects of the drive circuitry, the entire ForthDD product line is substantially and directly underpinned by PHYESTA innovations in optical sciences and materials processing. The collaboration with ForthDD remains active with Hossack and other staff continuing to consult and work with them.

PHYESTA/ERPE research [R6], was quickly incorporated into early products and has been continually developed and refined within the company to encompass higher colour depth, higher frame rates and higher definition. "*Thus every Forth Dimension Displays product, including the most recent product range, the QXGA (2048 x 1536 pixel) microdisplay launched in October 2012, has used and continues to use pulsed RGB LED illumination based upon the original ERPE scheme that was published [R2, R3] as an outcome of the foundational ERPE research."* CEO of ForthDD [F2].

5. Sources to corroborate the impact

[F1]	Director of Product Design at ForthDD. *Corroborates quote in Section 4*
[F2]	CEO of ForthDD. *Corroborates quote in Section 4*
[S1]	ForthDD web site: www.forthdd.com/ *Corroborates it is a leading supplier of microdisplays*
[S2]	Press releases from Kopin Corporation (parent company of ForthDD) www.kopin.com/press-releases/80-year.2011_80-id.150995321.html www.kopin.com/press-releases/80-id.150995339.html *Corroborates revenue and value of ForthDD at time of purchase in 2011*
[S3]	Scotsman article 11/10/13 on expansion of Microvue into Taiwan www.scotsman.com/news/microvue-in-163-20m-taiwan-investment-1-1383769 *Corroborates continuing importance of microdisplays to Scottish economy*