Institution: Edinburgh Research Partnership in Engineering – ERPE (Heriot Watt/Edinburgh)

Unit of Assessment: B15: General Engineering

Title of case study: Efficient, High Quality, Silicon Microdisplays

1. Summary of the impact (indicative maximum 100 words)

Micropix were formed in 1997 as a result of ERPE research (1993-08) into liquid crystal microdisplays. Following a major investment in 2004 the company was re-branded as Forth Dimension Displays (ForthDD).

Due to its unique microdisplay technology, based on the ERPE underpinning research, the ForthDD commercial activity has, since 2008, increased its annual revenue by more than 25% to around $5M and, over the same period, has increased its global workforce from 25 to 35 with exports to 15 countries.

Kopin Corporation, the world's largest producer of microdisplays, acquired ForthDD in 2011 for $11M.

2. Underpinning research (indicative maximum 500 words)

This ERPE research team comprised Professors: Underwood; Walton; and Stevenson (to 2012) and Smith (PDRA to 2012 then Lecturer) all in post throughout unless stated otherwise. Collaborators are: PDRA Bodammer and PhD students: Lee; Miremont; Rankin; and Seunarine. Associated Physics researchers are Senior Lecturer Hossack and Professor Emeritus Vass.

Introduction.
Liquid Crystal on Silicon (LCoS) spatial light modulators (SLMs) were conceived then researched and developed within ERPE and the School of Physics. The team developed high performance Ferroelectric Liquid Crystal on Silicon (FLCoS) SLMs in the late 1980s and early 1990s and deployed them in a range of applications with primarily industrial collaborators. [1] reports the state of the art of LCoS technology around 1993. Around that time it became clear that a major application for FLCoS SLMs was as miniature active-matrix liquid crystal displays (also called microdisplays) to be viewed under optical magnification in electronic projection systems and head-mounted display-systems.

The most important underpinning ERPE research contributions were:

Achieving colour without colour filters by pulsed illumination of red, green and blue LEDs.
To be successful in mainstream applications, a display technology must be capable of producing moving colour images. The first LCoS SLM-based microdisplays used single-colour LED illumination and so produced monochrome images. In 1996 a method for producing 3-bit colour images on a low resolution microdisplay using short rapid pulses of illumination from red, green and blue LEDs in sequence [2] was reported. The method was refined to produce 16-bit colour and high resolution [3] via the DTI-LINK project SLIMDIS (1995-7; ca £200k; with ERPE, GEC Marconi, Swindon Silicon Systems, Admit Design Systems, Davin Optical Holdings).

Improving image quality through improved manufacturing techniques.
Image quality is one of the most important factors in determining the competitiveness of a new display technology. Certainly a minimum level of image quality is essential. In the case of LCoS displays, the optical quality of the surface of the CMOS (active matrix) substrate has a huge influence on the perceived image quality. In the late 1990s this was the main topic of the EPSRC-funded PACMAN project (1998 – 2001; ca £800k; led by Underwood with Micropix, CRL, Admit Design Systems). [4] reported techniques to planarise the substrate at the pixel-array level (i.e., reduce excess curvature that can lead to colour artefacts). While [5] reports detailed process characterisation and optimisation to planarise the substrate at the sub-pixel level by filling narrow trenches in the substrate that, if unfilled, would adversely affect the alignment of the LC and,

thereby, the image quality.

Infrastructure for the design and characterisation of the technology.
A robust generic infrastructure for the design and characterisation of FLCoS microdisplays was an essential part of the industrialisation of the technology. This requirement was addressed in the EPSRC-funded ELITE project (1999-2001; ca £310k; led by Underwood with Micropix, GEC Marconi, Avant!, Domain Solutions). A key outcome, by way of example, was the development of an advancement to the widely used SPICE circuit description model for the FLC [6] which has made the overall design process much more efficient, accurate and robust.

3. References to the research (indicative maximum of six references)

References identified with * are those which best indicate the quality of the underpinning research.

[1]* Johnson, K.M., McKnight, D.J. and Underwood, I., "Smart Spatial Light Modulators Using Liquid Crystals On Silicon", IEEE Journal of Quantum Electronics, Vol. 29, No. 2, 1993. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=00199323 . Google scholar (GS) 187 citations.
This invited paper reports progress, state-of-the-art and future prospects for LCOS technology.

[2] Rankin, I.D., Underwood, I., Vass, D.G. and Worboys, M.R., "Full Colour Miniature Display", Proc SPIE on "Liquid Crystal Materials, Devices and Applications", Vol. 2651, pp. 16-24, 1996. http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=1013839 .
DOI (Full Proceedings):10.1117/12.235358. 10 GS citations.
First report of novel technique (field-sequential colour illumination) applied to a LC microdisplay to achieve energy-efficient full colour without the use of colour filters.

[3] Vass, D.G., Hossack, W., Rankin, I.D., Underwood, I., et. al., "A High Resolution Full Colour Head Mounted Ferroelectric Liquid Crystal-Over-Silicon Display", Ferroelectrics, Vol. 213, Issue 1-4, pp. 603-12, 1998. DOI:10.1080/00150199808016486. 10 GS citations.
The first high-resolution full colour FLCoS microdisplay-based head-mounted display system suitable for productisation.

[4]* Seunarine, K., Calton, D.W., Underwood, I., Stevenson, J.T.M., Gundlach, A.M. and Begbie, M., "Techniques To Improve The Flatness Of Reflective Micro-Optical Arrays" Sensors and Actuators, Vol. 78, pp. 18–27, 1999. DOI:10.1016/S0924-4247(99)00199-5. 14 GS citations.
Reports research to increase the image quality and energy efficiency of microdisplays by improving the flatness and fill factor of the in-pixel metal mirrors on the substrate.

[5]* Lee, Y., Parkes, W., Bodammer G. and Underwood, I., "Characterisation Of Inter-Metal Dielectric Deposition Processes On CMOS Backplanes For Liquid Crystal On Silicon Microdisplays", IEE Proceedings Optoelectronics, Vol. 151, No. 1, 2004. DOI:10.1049/ip-opt:20040137.
Reports detailed process characterisation and comparison for local planarization by filling trenches in CMOS active matrix substrates.

[6] Smith, S., Walton, A.J., Underwood, I., Miremont, C., Vass, D.G., Hossack, W.J., et. al., "SPICE Modeling Of Ferroelectric Liquid Crystal On Silicon Microdisplays", in IEEE International Conference on Microelectronic Test Structures, pp. 148-152, 2003 DOI:10.1109/ICMTS.2003.1197438.
Reports a SPICE circuit model that relates the electronic and electro-optical characteristics of the FLC.

4. Details of the impact (indicative maximum 750 words)

Since its formation ForthDD (originally Micropix) has raised in excess of $33M in investment including the 2011 injection of $11M by leading US microdisplay company, Kopin Corporation [S5]. Headquartered in Fife, Scotland, ForthDD has maintained and continues to maintain strong

technical links with the ERPE research team. 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 [S5]. Entirely digital, providing 24-bit full-colour images, capable of handling high-speed motion and with no visible artefacts, ForthDD'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. ForthDD now has offices in Spain, Germany and the USA.

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 [S1]. Underwood was employed as a consultant in the feasibility stage of defining the new product. *"ForthDD's premium quality components are deployed and used in the most demanding systems and applications imaginable. Forth Dimension Displays' product range has, from the beginning, been targeted at high-end markets. In these applications, image quality is of the utmost importance. The ability to provide colour has always been absolutely essential throughout our product range and the pioneering research done at ERPE on field sequential colour, using switched LED illumination, provided the foundation for our products to produce deep, saturated, satisfying colour."* CEO, ForthDD [S2].

The Near-To-Eye displays market comprises Head-Mounted Displays (HMDs) and Electronic Viewfinders (EVFs). While other companies and other divisions of Kopin address the mainstream, the Unique Selling Point (USP) of ForthDD is that its products achieve the highest image quality available in LCoS microdisplays and can thus command a high price from those customers with the most demanding applications. The foundations of the ability to meet the requirements of the most demanding applications lies in the research carried out by ERPE: *"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 ERPE research on backplane surface quality improvement. The backplane surface quality improvement techniques described by the ERPE 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 [S3].

Achieving colour with pulsed RGB LED illumination.

The combined fast switching capability of digital CMOS active matrix drivers and Binary Ferroelectric Liquid Crystal allowed the achievement of colour images by using fast pulses from Red, Green and Blue (RGB) LEDs to create the illusion of full colour images without colour filters and with no spatial separation of RGB sub-pixels. It also allowed an all-digital video signal path. This ERPE research [2, 3], 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 [2, 3] as an outcome of the foundational ERPE research."* CEO, ForthDD [S2]

Improving image quality through improved manufacturing techniques

The improvements in surface planarity and pixel fill factor achieved by ERPE researchers [4, 5], were critical to allowing FLCoS microdisplays 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 recently released product range rely upon the ERPE foundational research in manufacturing techniques pioneered in the Scottish Microelectronics Centre.

Infrastructure for the design and characterisation of the technology

The development of infrastructure linking the design and manufacturability of FLCoS microdisplays

(such as the developed SPICE model for the FLC [6]) assisted the productisation of the technology. "*GarField Matrics is the integrated circuit design subcontractor to ForthDD. ERPE researchers have made many successful technical advances to the design of FLCoS microdisplays. Specifically they developed a SPICE simulation model to represent the electrical load that the ferroelectric liquid crystal places on the drive circuit. It is essential to have SPICE models of components that are both robust and accurate. Thus the ERPE SPICE models have been used directly in the design of FLCoS active matrix backplanes. Thus the design-flow for new products has benefited directly from the ERPE research on design and characterisation*." Managing Director, GarField Matrics [S4].

The electronic architecture and pixel drive circuit of every product generation designed by ForthDD have been based upon architectures and designs first pioneered by ERPE researchers. Thus the prosperity of the company is comprehensively underpinned by ERPE research. And that prosperity is evident in that, today, ForthDD is the division of Kopin Corporation – the world's largest microdisplay company – whose products address the most demanding markets such as electronic viewfinders for professional cinematography cameras plus commercial and military flight simulators (97% of military flight simulators based on head-mounted displays use ForthDD microdisplays. Customers in these markets include Rockwell Collins, ARRI and L-3 Communications). Current products are focused on Virtual Reality [S6] for consumer applications.

"ForthDD develops and manufactures the world's highest performance microdisplays for use in Near-to-Eye and Head-Mounted Display Systems in market sectors such as aerospace, medical, training and defence. Operating in these very demanding market sectors, ForthDD has, since 2008, increased its annual revenue by more than 25% to $5M, almost entirely in exports, and over the same period has increased its global workforce from 25 to 35 employees, as well as providing competitive edge to its customer companies and benefits to the end-users of its display products. It now makes sales to 15 countries." CEO, ForthDD [S2]

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] http://www.forthdd.com/company/press-releases/2012/10/world's-highest-res the worlds highest resolution micro-display.

[S2] CEO, ForthDD, see comments included in Section 4.

[S3] Director of Product Design, ForthDD, see comments included in Section 4.

[S4] Managing Director, GarField Matrics Ltd., see comments included in Section 4.

[S5] http://www.kopin.com/press-releases/80-year.2011_80-id.150995321.html Kopin acquired Forth DD in 2011.

[S6] http://www.kopin.com/press-releases/80-id.150995339.html Replicating Reality™, provides the ultimate visual experience by making the user feel fully immersed in a virtual world, leading the way to revolutionise the consumer entertainment industry.