Institution: BRUNEL UNIVERSITY (H0113)

Unit of Assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: Fabrication of 3D electro-optic circuits by printing (FAB-3D)

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

Prof Silver's research on the development of the technology to fabricate 3D electro-optic circuits via ink-jet and screen printing has provided a more sustainable solution to conventional back-lit posters (energy saving up to 75%) and printed displays. Due to the flexibility of the components (they can be printed in any shape or design) and low maintenance (battery operational), the technology has been commercially exploited by several industrial collaborators. Johnson Matthey have used Brunel research to gain knowledge of the market and supply chain, to sell silver and palladium nano-particles for ink-jet printing and to inform the investment of around £2M on R&D in this area. Intrinsiq Materials Ltd successfully marketed copper-based inks for ink-jet printing of ACEL displays, allowing the company to employ 22 additional staff. In addition, they have secured $4M of venture capital investment to develop the technology. Printed Electronics Ltd have secured £8.6M of investment to develop a high-volume supply chain for printed electronics, and have employed an additional 9 staff within the company. As a result of working with Brunel, Keeling and Walker have begun to sell ink that contains antimony-doped tin oxide nano-powders.

2. Underpinning research (indicative maximum 500 words)

Prof Silver is the Executive Director of the Wolfson Centre for Materials Processing, which specialises in research in polymer processing technology and electronic display technologies. His research expertise is in inorganic nano-materials; phosphors and display materials; nano-particles; and printed electronics. His Phosphor and Display Materials Group is one of very few academic teams that have been carrying out systematic research on phosphors both as powders and thin films in recent times. The underpinning research has its origins back in 2006 when Prof Silver was finishing an EPSRC/DTI/Link grant on ACEL displays. Having taken a fresh look at ACEL displays, he threw out the old rules for making them and made a breakthrough in the research and design of flexible ACEL displays.[1] The new idea was to put the ACEL phosphor powder in a single binder layer that was extremely flexible and also acted as a dielectric layer. This removed the need for additional binder layers, making the displays much thinner so they could be used in a variety of new formats, allowing the building of very simple, cheap displays.[2-4] This led to a patent, as well as to new lines of research to understand the mechanism behind the ACEL phenomena. The initial publications attracted interest from several UK industries. This spurred on further research to understand the ACEL phenomena and the potential routes which led to further possible applications. During this time a UK company (Elumin8 Ltd.) contacted Prof Silver wanting to make more flexible and brighter ACEL displays. This led to TSB funding for the PLACES program and then (with further companies) the SHAPEL program. Fundamental research on the binder formulation, in particular on the effects of incorporating dielectric into the binder layer, so that the structure was a mono-layer, and then introducing a highly reflective background, showed how the brightness could be improved by over 50%.[5,6] Having made these breakthroughs in the underlying science, Silver realised that much of what had been done was applicable to 3-dimensional printing, and that with the latter it would be possible to research and then develop and envisage new materials to underpin new kinds of ACEL displays and printed electronic circuits. This led Prof. Silver to contact a number of companies to apply for a TSB project.

In the Technology Strategy Board-funded project 'Fabrication of Complex 3D Structures Using Direct Writing and Laser Annealing' (2008-11), Prof Silver brought together industrial partners such as Johnson Matthey (JM), Keeling & Walker Ltd (K&W), Oxley Development Company Ltd (Oxley), Intrinsiq Materials Ltd (IML), Printed Electronics Ltd (PEL) (industrial lead), and Nottingham Trent University. The project aimed to apply functional materials (often in nano-form) to various substrates (both flat and 3D), using printing methods (such as ink-jet, or screen printing) in order to fabricate electronic/optoelectronic circuits. One of the primary aims of the work was to examine the possibilities of ink-jet printing both hard and soft metal nano-particles.

Prof Silver and his team carried out the research and development of the functional inks that form the individual layers of multilayer devices such as AC electroluminescent lamps. They developed

all the functional inks used in the programme, and had input into the design of the architecture of the devices. They also characterised the structures produced using a range of techniques including scanning and transmission electron microscopy (SEM/TEM), surface analysis using x-ray photoelectron spectroscopy and x-ray powder diffraction. They successfully pioneered the screen printing of AC electroluminescent films onto ink-jet printed circuits, demonstrated them and then passed on the knowhow to Printed Electronics Ltd.[7] In addition, working demonstrators were produced which were acknowledged to give excellent performance.[7,8]

PEL were an excellent industrial lead and their expertise/knowhow in ink-jet printing was also fundamental for the successful outcome of the project. JM and IML both supplied, researched and developed metallic inks with PEL and Brunel. K&W supplied inorganic conducting nano-particles, Oxley needed new fabrication methods for producing high-end capacitances. Nottingham Trent University were involved in laser annealing the nano-particles.

The novel technology produced offers economic and sustainable advantages to existing technologies such as sputtering and aerosol spray pyrolysis. In particular the project demonstrated that metal particle inks can be printed in any desired configuration on various substrates such as ITO films and paper using ink-jet printers. The process is simple: ink-jet printers are used to print metal particle inks, and once the ink liquid vaporises, only metal particles are left; once exposed to high-intensity laser light, they sinter (the edges between them will join up). This process allows very fine detailed circuitry to be printed. The sintering process is low temperature and cheap. Screen printing processes were developed for laying electroluminescent layers on the printed electrodes to fabricate low-cost displays that could be operated with small batteries (so low maintenance). Once electricity is provided to the display circuits by the battery, they will light up on the paper. The printed circuits and electrodes can be copper but gold and silver also work well.

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

1) Low Cost, Flexible Electroluminescent Displays with a Novel Electrode Architecture Printed by Offset Lithography, R. Withnall, J. Silver, G.R. Fern, P.J. Marsh, T.G. Ireland, P.S.A. Evans, D.J. Southee, G.I. Hay, D.J. Harrison and K.F.B. Breen, International Symposium of the Society-for-Information-Display (SID 2008), Date: JUNE 7-9, 2006 San Francisco, California. *SID Digest,* 37, *1491-1494 (2006).* ISSN 0006-966X. http://dx.doi.org/10.1889/1.2433273

2) Correlating the ACEL performance of phosphor powders ZnS : Cu,X (X = Cl, Br) with their charge trap characteristics, J. Silver, R. Withnall, G. R. Fern, .P.J. Marsh, T.G. Ireland and A. Saliman, 13th International Display Workshop (IDW 06), Date: DEC 06-08, 2006 Otsu Japan IDW '06: Proceedings of the 13th International Display Workshops, VOLS 1-3 Pages: 421-422 (2006).

3) Printable inks and binders as vehicles for carrying/depositing phosphor nano-meter particles and ferroelectric nano-meter particles on screens for FEDs and EL devices, J. Silver, R Withnall, GR Fern, P. G. Harris, T. G. Ireland and A. Lipman, Chinese Journal of Electron Devices, 31(1) Pages 161-165, (Feb 2008), ISSN 1005-9490.
http://d.wanfangdata.com.cn/Periodical_dzqj200801041.aspx

4) Novel flexible EL powder displays, J. Silver, R. Withnall, GR; Fern, P. J. Marsh, T. G. Ireland and P. G. Harris, Proceedings of the 14th International Display Workshop, VOLS 1-3 Pages: 907-910 (2007).

5) Novel, flexible AC electroluminescent lamps for innovative display applications, J. Silver, R. Withnall, PG Harris, R Kirk, F Guinn, International Symposium of the Society-for-Information-Display (SID 2008), Date: MAY 18-23, 2008 Los Angeles CA 2008 SID International Symposium, Digest of Technical Papers, Vol. XXXIX, BOOKS I-III Volume: 39 Pages*: 182-185 (2008).* ISSN 0097-966X. (REF 2). http://dx.doi.org/10.1889/1.3069537

6) Structure and Morphology of ACEL ZnS:Cu,Cl Phosphor Powder Etched by Hydrochloric Acid, Robert Withnall, Jack Silver, Terry G. Ireland, George R. Fern, and Paul J. Marsh, Journal of the Electrochemical Society Vol. 156 *Issue:* 11 Pages: J326-J332 (2009). ISSN 0013-4651. (REF 2).

http://dx.doi.org/10.1149/1.3207950

7) Novel, bright, inorganic electroluminescent flexible displays comprising ink-jet printed silver back

electrodes, R. Withnall, P.G. Harris, J. Silver and S. Jones, SID Symposium Digest, vol. 41, 397-400 (2010). ISSN 0097-966X. (REF 2). http://dx.doi.org/10.1889/1.3500470

8)AC Powder Electroluminescent Displays; A state-of-the-art review., R. Withnall, J. Silver, P.G. Harris, T. G. Ireland and P. J. Marsh (2011), Journal of the Society for Information Display, 19 (11), 798-810: http://dx.doi.org/10.1889/JSID19.11.798

Grants

SHAPEL - Shape formable, Thin, ACEL Devices
Technology Strategy Board, 2008-2011, £518,364, PI J. Silver

FAB-3D - Fabrication of Complex 3-Dimensional Structures using direct Lighting and Laser annealing, Technology Strategy Board, 2008-2011, £937,253, PI J. Silver

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

The beauty of the printed electronics technology that arose from the FAB-3D is that it is capable of being used across a wide range of application areas. Printed electronic devices can range from emissive badges for people or instruments or even bottle labels, to displays for products, games, devices for security purposes, or even personal lighting devices such as light panels. It is also useful for short life-time products, where cheap devices are required for limited time periods such as for exhibitions or conferences, as well as for large-format devices such as advertising display posters. Another large area where the technology can be applied is on clothes as display panels or on safety helmets to act as nightlights.

The technology has been exploited by several industrial partners.

1) As a result of the FAB-3D project, Johnson Matthey has successfully sold precious metal nano-particles for making inks for the ink-jet printing of plastic electronics to a number of different customers. This has allowed them to understand the market and position themselves in the supply chain. They have invested over £2M in R&D to support this initiative.

http://www.jmsilver.co.uk/page-view.php?page_id=192&parent_page_id=178

2) Similarly, Intrinsiq Materials Limited (IML) has been selling copper based inks for ink-jet printing ACEL displays. They write "*…which have allowed the company to grow in size from 9 people in 2007 to 31 at the present time, and have secured an additional $4M of investment in the technology from US based venture capitalists. The help that we have received from Brunel has let us apply the technology to a large range of new applications winning both significant TSB and EU funding (approx. £5M to date) and more importantly a significant number of industrial customers. We have sold pastes and inks to over 100 companies, and as a result we are currently working on 8 joint development agreements to ready the technology for industrial applications in displays, electronics, solar cells, printed electronics and biotech."*

http://www.intrinsiqmaterials.com/Products.html

3) Printed Electronics Limited (PEL, Part of the Invotec Group of Companies) were the industrial lead of the project. They state that their "*staff have grown from 3 at the start of FAB 3D to 14 now and their biggest problem is getting qualified staff*." PEL are working with Hasbro to take embedded ACEL into board games. They further state that "*At the time there seemed to be nothing but problems but as we think back to where we were and where we are now we are pleased and proud of our achievements. Central to that achievement has been our relationship with you and your colleagues for which you have our thanks*." PEL have secured £8.6M of investment to develop a high-volume supply chain for printed electronics.

4) Keeling & Walker – supplier of inorganic nano-materials

In collaboration with Brunel, Keeling & Walker developed a novel spin-coating method for applying transparent conductive coatings on glass, based on an ink that contains antimony-doped tin oxide

nano-powders. Brunel's role was in the characterisation of the nano-powders during their development and full characterisation of the electrical and structural properties of the deposits. K&W now offer this ink for sale.

A limitation of the process was that it required substrates that could withstand the high temperatures necessary to cure the coatings. Initial collaborative studies between K&W, Brunel and Nottingham University indicated that the process could be operated on more temperature-sensitive materials by using a laser curing process, which had the added advantage of improving process times.

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

1) A letter received from Director, Government and Strategic Programmes, Intrinsiq Materials Ltd

2) A letter received from CEO, Printed Electronics Ltd.

3) A letter received from Technology Manager, Johnson Matthey Technology Centre

4) Contactable source: Managing Director, Keeling & Walker Ltd.