A complex multilayer screen-printed electroluminescent watch display on fabric

Marc de Vos, Russel Torah, Monika Glanc-Gostkiewicz, John Tudor

***Abstract*— A screen-printed electroluminescent digital watch display on fabric is presented. This work demonstrates the process of creating interactive printed smart fabrics suitable for a broad range of applications. In order to control the display, a series of tracks were printed that are 400µm wide with a pitch of 1mm; these dimensions are lower than the previously reported literature for connections to an EL lamp. An optimized design for a bus bar layer is designed, modelled and tested. The design improvement reduces the amount of the emitting area covered by an opaque conductor and is shown to have no negative impact on the function of the electroluminescent lamp. The design for the electroluminescent watch display includes 28 electroluminescent lamps on fabric forming four seven-segment displays. The display is the first demonstration of multiple EL seven-segment displays on fabric. The brightness is characterized and compared to commercially available blue electroluminescent lamps. The watch segments had similar brightness to commercially available lamps.**

***Index Terms*— Electroluminescence, electroluminescent devices, printed electronics, smart fabrics, e-textiles.**

I. INTRODUCTION

FLEXIBLE displays have seen significant development in recent years, with interest being driven by the expanding wearable technology market. In this work we demonstrate an entirely flexible electroluminescent (EL) watch display on fabric. The watch display is printed directly onto the fabric, significantly improving the ease with which displays can be integrated into existing clothing. This initial prototype assesses the feasibility of 28 printed EL displays close together on fabric to form a watch display.

EL lamps have been chosen for this device as they offer an entirely printable display technology [1-3]. The devices work by forming a capacitor structure with a phosphor in the middle as the emitting layer. A dielectric is also included in between the electrodes to prevent short circuits, and one of the electrodes is printed using a semi-transparent conducting material to allow light out of the capacitor structure. A full description and diagram are included in the EL watch design section. EL lamps are also more durable than many other display technologies.

The device is printed layer by layer with thicknesses for each layer ranging from 15 microns to 200 microns, and are tolerant to variations in layer thickness without affecting device performance.

An alternative approach to printing light emitting displays has been demonstrated by Jabbour et al, in which organic light emitting diodes (OLEDs) were screen-printed [4]. Only the hole transport layer was screen-printed whereas in this present paper, all layers of the structure are screen-printed, meaning production time is faster. The work by Jabbour et al also showed the printed layers were 10-50nm, which is much thinner than the thick-film EL lamps in this work meaning they will not be as durable. OLEDs also usually require special controlled atmospheres during production making fabrication more complex and expensive [5].

A single EL lamp partially screen-printed onto fabric was shown by Sloma et al [6]. The last layer of the structure was spray-coated meaning the device was not fully screen-printed. The devices on fabric were visually unattractive with sections of the lamp not illuminated and visible cracks in the inks.

A more recent approach demonstrated by the authors uses a pneumatic syringe on moving stages (dispenser printer) to deposit layers for an EL lamp [2]. This approach is not suitable as a display due to the small feature sizes (~400µm) required to pattern four seven-segment displays closely together.

Screen-printing is a process that has been developed over the last 1000 years and is particularly suited to mass production [7]. Screen-printing deposits a film of paste in a desired pattern, defined by the screen, with a controlled thickness. The paste is deposited through a mesh reinforced stencil, called a screen, using a rubber squeegee to apply a downwards pressure onto the paste. The process of screen-printing is a multi-stage process consisting of the following steps:

1. Paste is spread over the screen that is held just above the substrate.
2. A squeegee applies pressure to the screen and moves across the design forcing paste through the screen in the desired pattern, defined by the screen, onto the substrate below.
3. The screen is removed leaving the film of paste on the substrate.

An important part of the screen printing process is maintaining a 'snap-off distance' above the substrate, with contact between the screen and substrate only being made

Paper was submitted on: May 3, 2016

M. de Vos, with the School of Electronics and Computer Science, University of Southampton, Southampton, SO17 1BJ, UK (e-mail: mdv1g10@soton.ac.uk).

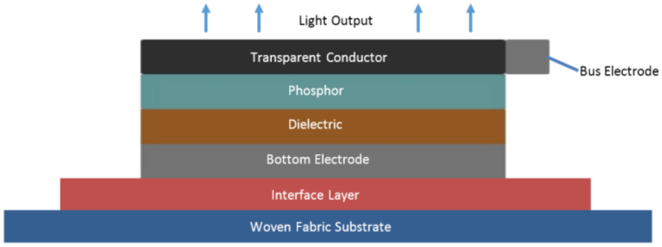

Fig. 1 Cross-section diagram of an EL lamp with interface layer.

where the squeegee touches. This is required to maintain a high quality print as it prevents the paste bleeding outside the desired print area.

Many factors affect the print thickness and quality when screen-printing, particularly the screen mesh, paste rheology, squeegee hardness, substrate, printing process and printing machine [8]. Screen-printing has been selected as the fabrication method for this work as it is a very accurate deposition method that has been previously shown to achieve electroluminescence on fabric [1]. An accurate fabrication method is key to achieving an EL watch as the tracks are 400 microns wide and the device includes six layers that must all be aligned. Screen-printing is also suitable to use with a wide range of inks. Acceptable ink viscosities range from 3 to 350 Pa.s. depending on the paste manufacturer [9-11]. The maximum particle size is defined by the screen being used, typically the screen mesh opening should be 2-3 times larger than the particles in the paste. Using screen-printing ensures that mass production of the EL watch using the process described in this paper should be relatively straight forward as it is compatible with roll-to-roll processing.

In this work novel EL connecting silver tracks are presented with reduced dimensions compared to the literature, along with an improved bus bar design that results in the emitting area being 32% larger for the EL lamp size used in this work. The improvements are demonstrated in an EL device that is the first demonstration of multiple seven-segment EL displays.

II. EL WATCH DESIGN

EL lamps are formed from six printed layers, each cured after deposition. A cross-section diagram of an EL lamp is shown in Fig. 1 above. Each printed layer is described below:

1. Interface layer - The interface layer is printed first and aims to smooth the fabric surface to allow subsequent layers to be printed with improved homogeneity compared to printing directly on fabric [12].
2. Bottom electrode - The bottom electrode provides one half of the capacitor structure. High conductivity is important to provide sufficient distribution of charge over the electrode [13].
3. Dielectric layer - The dielectric layer is printed on top of the bottom electrode. The layer covers the entire electrode with an overlap and is designed to prevent short circuits between the electrodes. The dielectric is also usually white in colour as it then also acts as a reflector for any light emitted into the device.
4. Phosphor layer - the phosphor particles emit light when under the influence of a high strength alternating electric field (around 3MV/m).
5. Bus electrode - The bus electrode layer provides connectivity to the top electrode. It is printed using the same paste as the bottom electrode.
6. Transparent conductor – The transparent conductor forms the top electrode and completes the capacitor structure.

The EL watch in this work includes only the display; the control electronics are separate to simplify the design. The watch display is printed directly onto the fabric which can then be cut out into any desired shape, a diagram showing a summary of the layout can be seen in Fig. 2. A limitation of the printer used in this work is that the maximum print area is 15x15cm. The watch strap needs to be longer than 15cm to form a continuous loop around a wrist, so in this work the watch is attached to a second piece of fabric to complete the strap. This would not be a limitation if the watch were to be mass produced on a larger commercial printer.

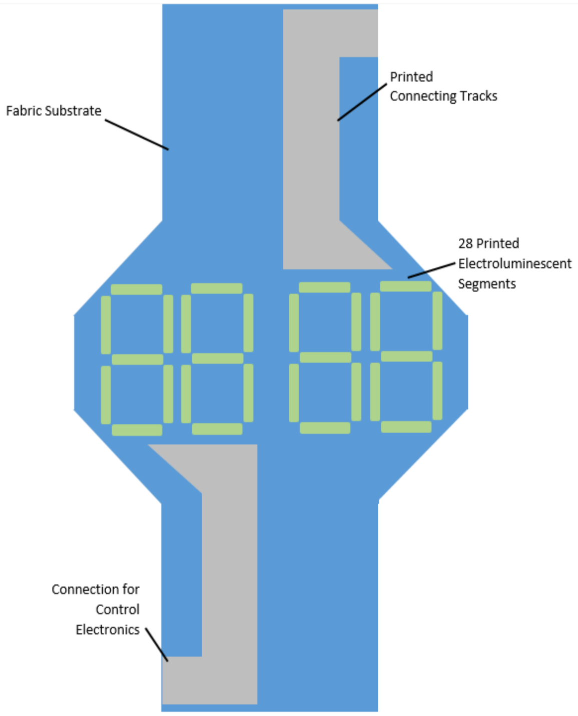

Fig. 2 Diagram of printed EL watch layout.

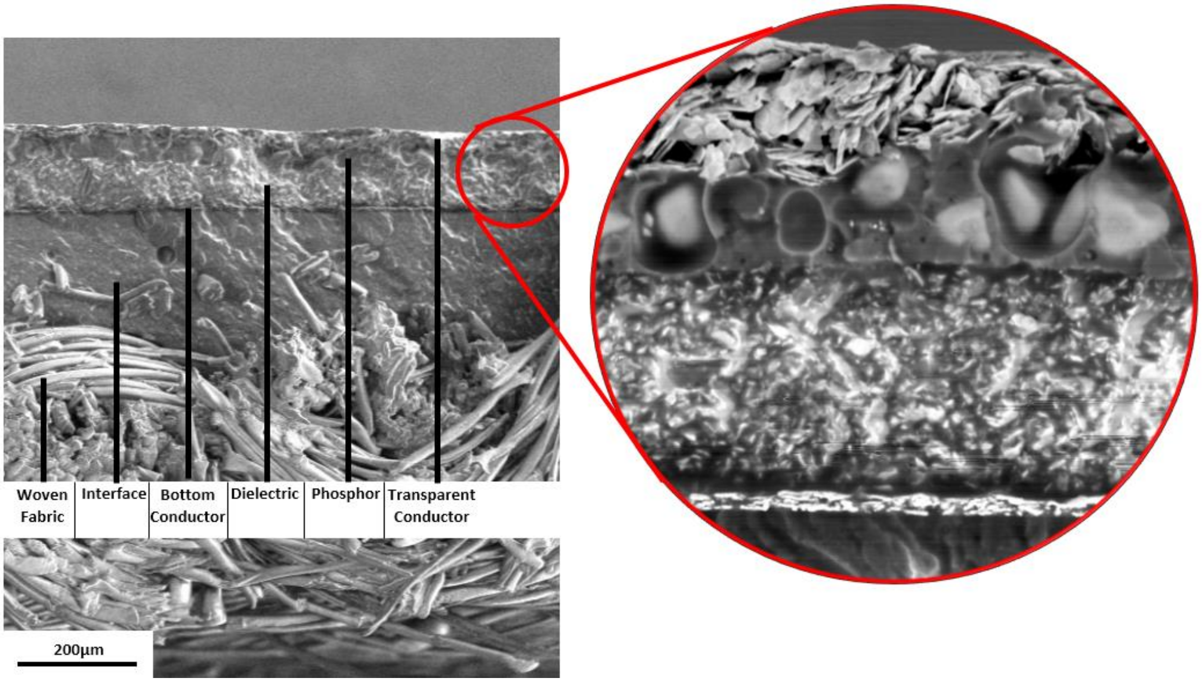

Fig. 3 EL lamp with interface layer printed onto polyester cotton, with a close up view of the printed EL lamp layers in the circle

The screen-printing process also places limitations on the minimum pitch of the connecting tracks. Each of the 28 EL segments used in the watch requires a separate connecting track with two additional tracks to power the two common bottom electrodes, meaning a total of 30 connecting tracks are needed. The tracks in this work are the narrowest with the lowest pitch of any in the literature used to connect to an EL lamp. The tracks are not directly comparable to any printed silver tracks as they must be capable of carrying the high voltage required by the EL lamps. The tracks are 1mm pitch with 400µm tracks. Below this thickness the tracks either bleed into each other creating short circuits or they prove unreliable during flexibility testing. Narrow tracks with a low pitch are important as it directly affects the number that can be fitted into a defined area. In this work it was important to fit many tracks into a small area to avoid an oversized ‘watch strap’ that would be visually unappealing. To aid alignment of the layers during printing, triangular alignment marks are used. The dielectric also incorporates a 550µm overlap to prevent a short circuit if there is some misalignment.

For this work a 65/35% blend polyester-cotton supplied by Klopman Srl will be used as the fabric substrate. This fabric was selected because it is widely used in clothing applications and has typical fabric properties with regards to weave, heat tolerance and texture. However, it is also difficult to print homogenous layers of material directly onto it due to its high surface roughness and loose fibres in the yarn structure, known as pilosity. To counter these fundamental problems an interface paste has previously been developed at UoS that is designed to smooth the rough fabric surface to an acceptable level, whilst maintaining the original fabric properties where possible. Fig. 3 above shows an SEM cross-section of the woven polyester cotton fabric used in this work with an EL lamp printed on top of it. The EL lamp makes use of the interface layer and its smoothing properties can clearly be seen.

The difference in surface roughness was quantified using the Alicona Infinite Focus to measure the roughness (R_a) values. The polyester cotton fabric on its own has a roughness of 30.7µm, while the roughness of the same fabric with a printed interface layer was 1.5µm. This improvement in surface roughness is sufficient when considering that the printed functional layers are typically 10-40 microns thick. Thus the interface will allow for more consistent functional performance as well as providing encapsulation from the back of the fabric.

In a typical EL lamp a high conductivity bus bar placed around the perimeter of the EL lamp [14]. Silver ink is commonly used for this purpose in printed EL lamps as it is a readily available ink with high conductivity and is usually also used for the bottom electrode. The bus bar is typically printed around the entire perimeter of the EL lamp helping to distribute the charge across the lower conductivity semi-transparent conductor more evenly. In large EL lamps, if this layer does not cover the perimeter then a dimming effect would be present, away from the point where the high conductivity layer connects to the semi-transparent conductor [14].

When printing small area EL lamps (<2cm^2) the bus bar can occupy a significant percentage of the overall design area. An example screen design for a single segment from a seven-segment display is shown in Fig. 4 below. The segment has a height of 3mm and the bus bar track width is 400µm, the

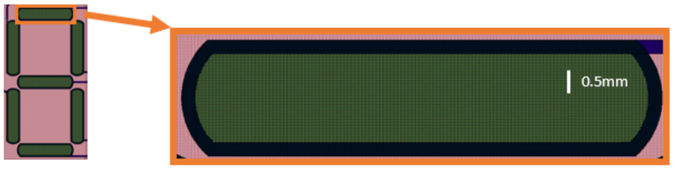

Fig. 4 A seven-segment display design (left) with a magnified single segment image (right) highlighting the large percentage of the emitting area of the lamp covered by the opaque bus bar (black area).

minimum that can reliably be screen-printed on fabric. As the design includes a perimeter bus bar, approximately 32% of the segment area is non-emitting as it is covered by this opaque conductor. This design limits the minimum size of segment that can be produced whilst maintaining visibility.

As an example, a printed 3 x 3cm EL lamp with a bus bar around the entire perimeter would mean that the percentage of emitting area covered is not significant as it is a much larger EL lamp than those used in the EL watch display. However, the amount of silver ink used with the full perimeter bus bar was 1800nL, this could have been reduced to 37.5nL if a small 2.5mm long bus bar was used instead, a reduction of 98%. This is significant when high value inks (like silver ink) or large numbers of EL lamps are printed. The print time would also see a reduction from 12.5 seconds for the full perimeter bus bar, to 0.75 seconds for a 2.5mm single side bus bar.

A simple COMSOL model was built of the EL lamp and the voltage drop over the transparent conducting layer was simulated with a bus bar around the entire perimeter and a shorter 2.5mm bus bar. The results are shown in Fig. 5 and suggest there would be a 30% voltage drop at the furthest point with the inks in use, even with short (<2.5mm total length) bus bars on 1 x 2cm EL lamp. A 30% drop in voltage is unlikely to cause a drop in brightness that is noticeable to the human eye, therefore a practical test was carried out. A series of EL lamps were then printed using a dispenser printer to test whether the bus bar is required around the perimeter of the lamp for the designed sizes. The dispenser printer was used as it's able to quickly produce EL lamp prototypes in simple shapes with different designs [3]. Using this rapid prototyping method avoids the purchase of expensive screens which are not well suited to interim testing. The dispenser printer is not suitable for mass production due to the low speed and throughput compared to screen-printing but it is ideal for these bespoke design tests. The dispenser printer uses the same inks with similar thicknesses, meaning the test is also applicable to screen-printed EL lamps. The emitting area of the test lamps is 1 x 2cm, with a bus bar connection only on the bottom of the emitting area. The length of the bus bar along the bottom of the lamps was varied according to Table 1. The printed EL lamps are shown in Fig. 6.

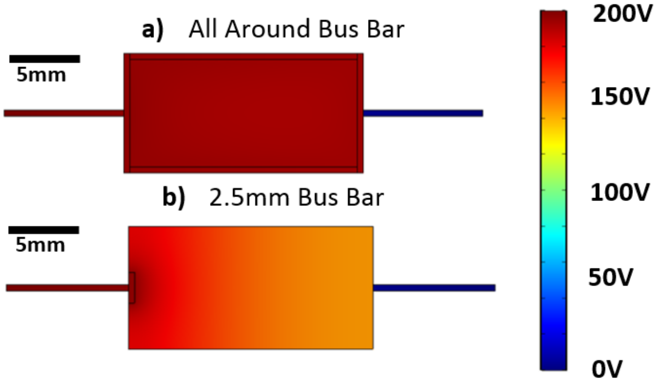

Fig. 5. Images showing the COMSOL model results for a bus bar around the entire perimeter (a) and a 2.5mm reduced size bus bar (b).

TABLE I
LENGTH OF THE SILVER BUS BAR ALONG THE BOTTOM OF THE EL LAMP FOR EACH OF THE FIVE SAMPLES

Sample	(a)	(b)	(c)	(d)	(e)
Bus Bar Length (mm)	*0*	*2.5*	*5*	*7.5*	*10*

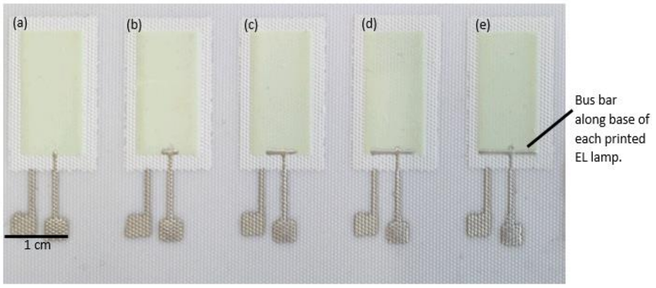

Fig. 6 Five dispenser printed EL lamps (a-e) showing bus bars along the bottom edge of 0mm, 2.5mm, 5mm, 7.5mm, and 10mm respectively. In this image no transparent conductor layer has been printed to clearly show the bus bar lengths.

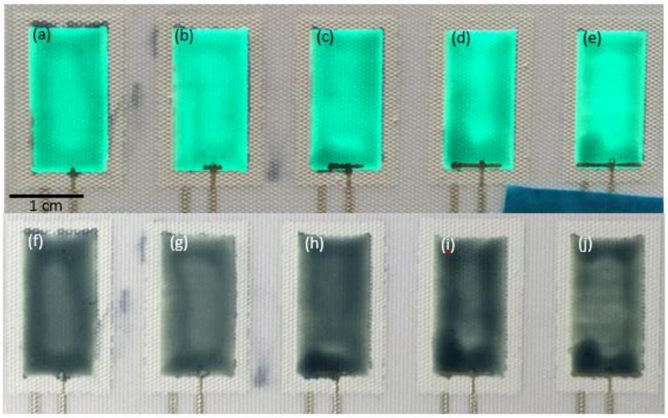

Fig. 7 Five dispenser printed EL lamps, powered (top) and unpowered (bottom).

The lamps were tested simultaneously using a Supertex HV881 driving circuit to allow a consistent comparison and to avoid any variations in ambient light [15]. The driving circuit is available commercially and is capable of driving up to 16 1nF load EL segments simultaneously from an input voltage of 5V. In order to drive all 28 segments on the display, two of these drivers were used. Custom microcontroller code was written to address each of the devices using the I^2C protocol. The five EL lamps can be seen powered and unpowered in Fig. 7 above.

Fig. 7 shows all of the lamps are functional and that there is no dimming away from the bus bar situated on the bottom edge. The slight dimming pattern away from the centre seen in Fig. 7(a) can be attributed to the non-uniform layer thickness, which is visible when unpowered Fig. 7(f). Similar patterns can be seen in some of the other samples as printing the semi-transparent conducting layer was challenging when using the dispenser printer. The voltage drop away from the bus bar predicted in the model is not visible due to variations in the printed layers dominating what is visible.

If the lamp design in Fig. 4 had used this smaller bus bar design and only connected to one short side of the EL lamp,

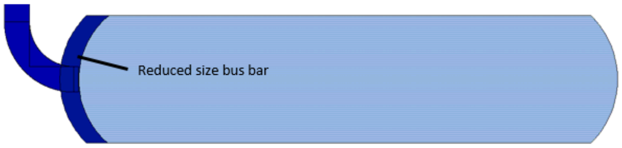

Fig. 8 Image showing the design of the improved EL lamp segment with shortened bus bar.

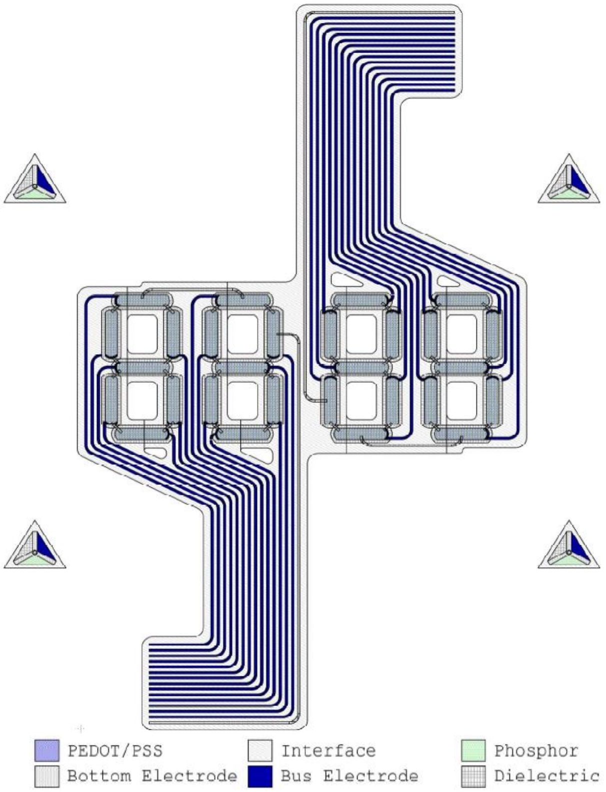

Fig. 9 Design for the screen-printed EL watch display.

TABLE II
LIST OF THE INK USED FOR EACH PRINTED LAYER

Layer Name	Ink Used
Interface	*FabInks UV-IF1004*
Bottom Electrode	*FabInks TC-C4001*
Dielectric	*FabInks TC-D9001*
Phosphor	*FabInks TC-P0001*
Transparent Conductor	*FabInks TC-C4006*
Bus Electrode	*FabInks TC-C4001*

the percent of emitting area covered by the bus bar would have been reduced from approximately 32% to 4%. The results allow the EL watch to be designed with a single small connection at the edge of the PEDOT:PSS layer.

The bus bar design used for the EL watch is shown in Fig. 8. The final EL watch design has similarities to a typical four-digit digital watch. It includes 28 individually controllable segments and has cut outs in the interface layer where no further layers are printed to maintain flexibility and breathability. The tracks incorporate an ‘L’ shape to allow for easier connection of the control electronics when the device is sewn onto a watch strap. The ‘L’ shape is required because the top and bottom ends of the fabric will not be accessible to the connecting electronics as it will be sewn down onto another fabric. The triangular patterns are alignment marks for each layer to help with the printing, they have no electrical function. The full design is shown in Fig. 9.

III. EL WATCH FABRICATION

The inks used to print each layer were selected from the Smart Fabric Inks Ltd range [16]. These inks were chosen as they are all compatible with use on fabric and the screen-printing process. The inks used for each layer are shown in Table 2 above. Each layer was consecutively screen-printed

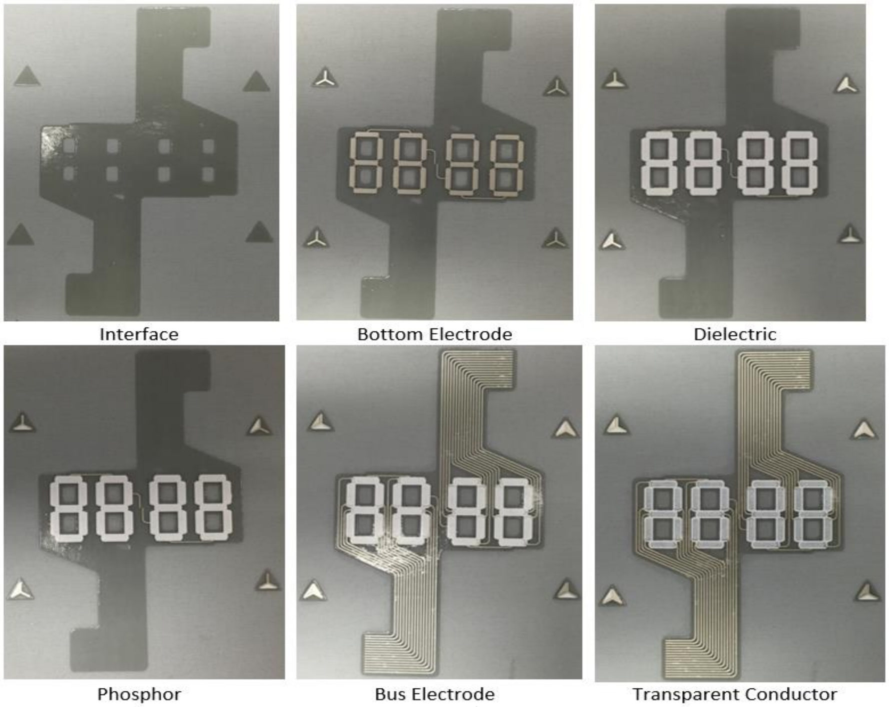
Interface
Bottom Electrode
Dielectric
Phosphor
Bus Electrode
Transparent Conductor

Fig. 10 Images showing the EL watch after each consecutively printed layer.

onto a polyester cotton fabric mounted on an alumina tile. The alumina tile was used to ensure accurate alignment between each printed layer. Before each layer was printed the tile was pushed against four alignment pins on the screen printer. Images showing the EL watch after each printed layer are shown in Fig. 10 above.

IV. RESULTS AND DISCUSSION

The EL watch functionality was tested, along with the luminance of the lamp at a variety of driving voltages and frequencies. During functionality testing the watch was powered using two Supertex HV881 multi-segment EL drivers [15], with each driver powering two of the digits (14 segments). Software was written to control the HV881 chips using I^2C to give watch like functionality. A TTI TGA1241 signal generator and Trek PZD700 power amplifier were used for testing the lamps at various voltages and frequencies. The luminance measurements were taken using a Konica Minolta CS-100A luminance meter in a darkened room to ensure the results were not affected by ambient light sources.

All four watch segments were tested by showing the time, this is shown in Fig. 11(a) below. For testing the watch was connected using a custom 3D printed connector with the correct wire pitch, however, if commercially developed the watch could be used with a bespoke zero insertion force (ZIF) connector. The watch segments were sufficiently bright to be seen in normal ambient light in laboratory conditions. Fig. 11(b) shows the watch in a potential application integrated into a sleeve.

The EL watch display was tested across a range of driving voltages and frequencies. The Supertex HV881 driver used to light all of the segments is capable of driving at voltages up to $400V_{peak}$ and frequencies up to 2000Hz, so a range of driving voltages up to these levels were tested. A higher driving voltage and frequency are known to lead to a quicker degradation of the phosphor particles [13]. The light output was tested from 50-400Vpeak and 200-2000Hz driving frequency and the results are shown in Fig. 12. A 200V peak voltage at 400Hz would be typical for an EL lamp driver. The results for the luminance of the screen-printed EL lamp are approximately half those recorded on a previous screen-printed EL lamp [2]. The disparity is thought to be caused by the long silver tracks leading to the EL lamps. The test in the literature had the a short 5mm silver track leading to the EL lamp, whereas the EL watch display has track lengths of approximately 100mm. The voltage drop over these longer tracks is likely to be the primary cause of the lower luminance. The transparent conducting layer also had a lower print quality with an imprint of the screen-mesh still visible, causing a slightly lower luminance.

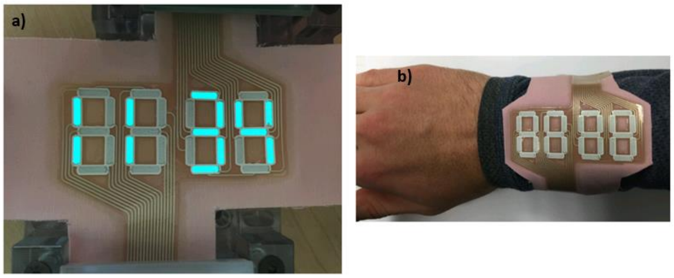

Fig. 11 (a) EL watch powered using a Supertex HV881 driver and connected using a custom 3D printed connector. (b) EL watch integrated into the sleeve of a jumper.

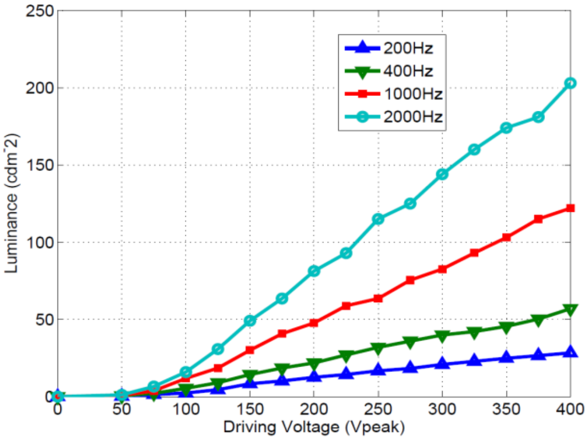

Fig. 12 Luminance data for the EL watch across a range of driving voltages and frequencies.

The results from the EL watch are similar to blue colored commercial EL lamps previously tested [3] that showed a luminance of 20.5cd/m^2 at 200Vpeak/400Hz, while the EL watch demonstrates 21.8cd/m^2 at the same voltage and frequency.

To enhance the lifetime of the EL watch, a driving voltage of $150V_{peak}$ at 400Hz was selected as it was sufficient to be easily visible in ambient light. Previous studies have suggested lifetimes of up to 10,000 hours can be achieved at these emission levels [13]. The EL watch was shown previously in Fig. 11(a) under these driving conditions.

V. CONCLUSIONS

A prototype screen-printed EL watch has been demonstrated with 28 individually addressable lamps; significantly more complex than previous work [1] and as far as the authors are away the only example in the literature. The watch display utilizes tracks that are 1mm pitch and 400µm width, this is narrower that any in the literature for an EL lamp. Being used to drive an EL lamp means the tracks must be of sufficient quality to carry voltages up to 400V.

The EL lamps have been combined to form a novel watch display that is entirely printed onto fabric using six consecutive printed layers. In order to enable functional multilayer printing an interface layer has been deposited to significantly smooth the fabric surface roughness. The work also includes a novel bus bar design that has been modelled and tested. It is shown to enable smaller EL lamps to be fabricated than have been achieved in the literature. The EL lamps are also more closely spaced presenting unique design opportunities.

This work represents the first time printed EL lamps have been combined to form a watch display on fabric and offers exciting possibilities for further integration of electronics into clothing. To further improve the integration different coloured fabrics could be used, an inkjet image could be printed onto the fabric as well with printed EL lamps integrated within it, or different coloured EL lamps could be used.

DATA

All data supporting this study are openly available from the University of Southampton repository at dx.doi.org/10.5258/SOTON/390695

REFERENCES

[1] M. de Vos, R. Torah, S. Beeby, and J. Tudor, "Functional Electronic Screen-printing – Electroluminescent Lamps on Fabric," in *Eurosensors*, 2014, pp. 1513-1516.

[2] M. de Vos, R. Torah, and J. Tudor, "A Novel Pneumatic Dispenser Fabrication Technique for Digitally Printing Electroluminescent Lamps on Fabric," in *DTIP 2015*, Montpellier, France, 2015.

[3] M. de Vos, R. Torah, and J. Tudor, "Dispenser Printed Electroluminescent Lamps on Textiles for Smart Fabric Applications," *Smart Materials and Structures* 2015.

[4] G. E. Jabbour, R. Radspinner, and N. Peyghambarian, "Screen printing for the fabrication of organic light-emitting devices," *IEEE Journal of selected topics in quantum electronics,* vol. 7, pp. 769-773, 2001.

[5] X. Tao, *Wearable electronics and photonics*: Elsevier, 2005.

[6] M. Sloma, D. Janczak, G. Wroblewski, A. Mlozniak, and M. Jakubowska, "Electroluminescent structures printed on paper and textile elastic substrates," *Circuit World,* vol. 40, pp. 13-16, 2014.

[7] A. Hobby, "Screen-Printing for the Industrial User," DEK Printing Machines Ltd1997.

[8] J. Pan, G. L. Tonkay, and A. Quintero, "Screen printing process design of experiments for fine line printing of thick film ceramic substrates," *Journal of Electronics Manufacturing,* vol. 9, p. 203, 1999.

[9] (1 Feb). *DuPont LuxPrint 8155 Phosphor Vehicle*. Available: http://www2.dupont.com/MCM/en_US/assets/downloads/prodinfo/8155.pdf

[10] (1 Feb). *DuPont LuxPrint 9145 Silver Conductor*. Available: http://www.dupont.com/content/dam/dupont/products-and-services/electronic-and-electrical-materials/documents/prodlib/9145.pdf

[11] (1 Feb). *ESL Electroscience 33000 Resistor Paste*. Available: http://www.electroscience.com/pdf/33000.pdf

[12] K. Yang, R. Torah, Y. Wei, S. Beeby, and J. Tudor, "Waterproof and durable screen printed silver conductive tracks on textiles," *Textile Research Journal,* vol. 83, pp. 2023-2031, November 1, 2013 2013.

[13] M. Bredol and H. Schulze Dieckhoff, "Materials for powder-based AC-electroluminescence," *Materials,* vol. 3, pp. 1353-1374, 2010.

[14] (22 May). *Processing Guide for DuPont Luxprint EL Inks*. Available: http://www.dupont.com/content/dam/assets/products-and-services/electronic-electrical-materials/assets/datasheets/prodlib/EL_Processing_Guide.pdf

[15] S. Inc. *Electroluminescent (EL) Backlight Driver ICs*. Available: http://www.supertex.com/pdf/misc/el_driver_ics_SG.pdf

[16] (1 Feb). *Smart Fabric Inks Ltd*. Available: http://www.fabinks.com/

Marc de Vos graduated with a BEng(hons) in Electromechanical Engineering in 2013 from the University of Southampton and is currently in the third year of a PhD in Electronics, also at University of Southampton.

Mr de Vos' PhD focuses on printed electroluminescent lamps on fabric and dispenser printing. Mr de Vos has four publications.

Russel Torah graduated with a BEng(hons) in Electronic Engineering in 1999 and an MSc in Instrumentation and Transducers in 2000, both from the University of Southampton. Between 2001 and 2004 Russel obtained a PhD in Electronics from the University of Southampton in the optimisation of thick-film piezoceramics.

Since 2005 he has been a full time researcher at the University of Southampton where he is currently a Senior Research Fellow.

Dr Torah is a co-founder of the Smart Fabric Inks (in 2011) company specialising in printed smart fabrics. Dr Torah's research interests are currently focused on smart fabric development but he also has extensive knowledge of energy harvesting, sensors and transducers. Dr Torah has 80 publications.

M. Glanc-Gostkiewicz obtained her MSc in Soil Science in 2002 from Nicolaus Copernicus University, Poland. After graduating she moved to the United Kingdom where she studied at the University of Portsmouth and received a PGCE qualification.

Dr Glanc-Gostkiewicz subsequently taught for three years in secondary schools in Hampshire. In 2016 she obtained a PhD in Electro-mechanics from the University of Southampton. Her project aimed to design low-cost and miniaturised thick-film chemical sensors for water quality monitoring. Monika has 11 publications.

John Tudor graduated with a BSc(Eng) in Electronic and Electrical Engineering from University College London in 1983. Between 1984 and 1988 John obtained a PhD in Physics from Surrey University in optics, MEMS and sensors. He worked concurrently as Research Engineer at Schlumberger Industries during 1988 where he remained until 1990, spending the last year at their Global Research Centre in Paris. Between 1990 and 1994 John was an academic at Southampton University, on a part time basis during 1994 whilst leading the Microengineering group at ERA Technology, where he remained until 2001. Since 2001 he has been a full time researcher at Southampton University where he is currently a Principal Research Fellow. Dr Tudor is a co-founder of the companies D4 Technology (in 2001), Perpetuum (in 2004) and Smart Fabric Inks (in 2011). Dr Tudor's research interests are currently smart fabrics, printing, energy harvesting, sensors and MEMS. Dr Tudor has 125 publications and 11 patents.