Double sided roll-to-roll manufacture of flexible display panels

C. Williamson[1], H.-L. Liang[1], Stuart Speakman[2], D. Chu[1]

(1. *Centre for Advanced Photonics and Electronics*, *Engineering Department*, *University of Cambridge*, 9 *J. J. Thomson Ave.*, *Cambridge CB*3 0*FA*, *UK*)

Abstract: A double sided roll-to-roll (R2R) system has been developed by the authors to automate the continuous manufacturing of flexible display panels. Here we report an overview of the system operation and the fabrication process. The system framework features a timer initiated slot-die coating followed by wet lamination to form a thin, active layer in between flexible conductive substrates. A rotary screen-printing unit is installed for adhesive deposition providing an edge seal for the panel. The system enables production of 15-cm^2 laminated panels.

Key words: Roll-to-roll; displays; manufacturing; liquid crystal; printing; flexible

1 Introduction

In the drive to make ubiquitous technology, it is necessary to reduce production costs and increase throughput. Roll-to-roll (R2R) manufacturing offers a viable alternative for high-tech industries and there is currently a push to move processes in this direction.

R2R processes require a flexible substrate which in turn has instigated significant innovation to introduce improved product capabilities and weight savings alongside cost and speed benefits. Organic electronic devices have ideal properties for R2R and at an early stage in their design it was suggested that being able to produce these devices on a continuous R2R system would be the ultimate goal[1]. The best organic photovoltaic (OPV) cells are over 10% efficient[2] however the optimal power conversion efficiency and lifetime stability is often traded for the ability to produce cells on a R2R system[3-6].

R2R processes have been used for a wide variety other of devices including printed transistors[7] patterned organic RFID tags and ring oscillators[8] and the processes commonly used in these devices are solution based print methods which are compatible with low temperature plastic substrates and highly scalable. In order to deposit certain metallic or ceramic coatings, in-line sputtering[9] or evaporation[10] is possible.

Early stage technologies, such as grapheme[11] and carbon nanotubes (CNTs)[12], which have the potential to revolutionise electronic devices, are also being tested for compatibility with R2R manufacturing since it is realised that traditional batch processes are currently a limiting factor for mass production. Time taken during start-up and shut-down is highly wasteful and it has also been reported that a R2R process for CNT fabrication consumes approximately 90% less gas and is 26 times faster than batch processing of the same device[13]. This offers improved potential for industries to meet environmental and production targets for new and innovative production lines.

At the time of writing, it would appear that all R2R processes have been carried out on a single film. This mechanism is sufficient for certain devices where a basic structure without passivation is being fabricated, however the single sided approach is suboptimal where additional layers are required. This is particularly applicable in display manufacture where a material such as liquid crystal is enveloped between two films. One approach is to attach separate films over each panel on the R2R line[14] however this requires accurate alignment which can be challenging on plastic substrates[15] and is also likely to induce air into the panel.

The advantages of double sided lamination have been demonstrated[16] but tests use stand-alone systems rather than a continuous process. Cheng-Yao et al. present an ideal R2R system using two separate webs which are laminated together in the final part of the process[17] however the practical process is non-continuous and involves unwinding and rewinding the rolls separately for each process stage[18].

Here we present a continuous double sided R2R system where processing can be carried out on two separate webs before being laminated together to form a single sealed panel which is free of air bubbles. Parallel processing is enabled through the use two separate films, and multilayer film alignment is eliminated since the laminated films are cut out during the final stage.

2 Framework

2.1 System requirements

The two main requirements for the R2R system design were increased production speed and improved control of the process. This demands continuous control of the film tension and speed alongside adjustment and monitoring of component temperature. The ability to enable and disable system components was also required and each aspect of the system needed to be controlled by a graphical human-machine interface (HMI) to ensure operation is intuitive for the user. The resultant system can be seen in figure 1.

Fig. 1 R2R Framework

The system has been designed to laminate a smectic-A liquid crystal layer with a working thickness of approximately 15-μm between two transparent indium tin oxide (ITO) coated polyethylene terephthalate (PET) films. The resultant laminated film then requires cutting into 15 cm^2 panels which have the facility for electrodes to be attached. An important specification for the system was that it is primarily to be used for research purposes. This has the added implication that there must be sufficient additional space for components to be added in future, and it also requires precise control at low speeds.

To achieve the required panels, two rolls of film are fixed to powered unwind rollers and these are then fed through a series of processes. The first step is to screen print an adhesive annulus which is subsequently filled in with liquid crystals from a slot-die coater. The two ITO-PET films are then laminated and at the end of the process a die cutter cuts out a cell and the remaining waste film is rolled onto a rewind roller. The path of the web is shown in figure 2.

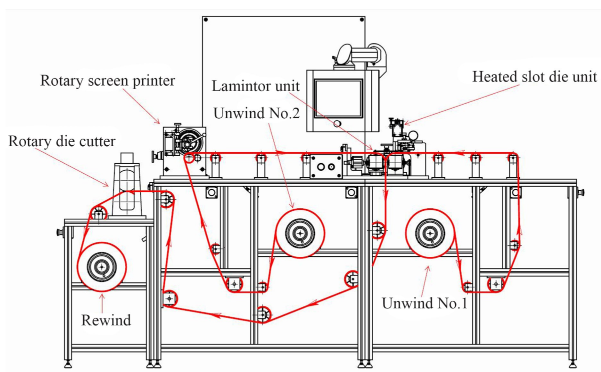


Fig. 2 Roll to roll framework showing the direction (indicated by the bold arrowed red lines) of the web

2.2 Film control

During research stages the film is operated at relatively slow speeds between 100 ~ 1000 mm/min where the drive is provided by servos connected directly to the heated steel lamination roller (Fig. 3, location B).

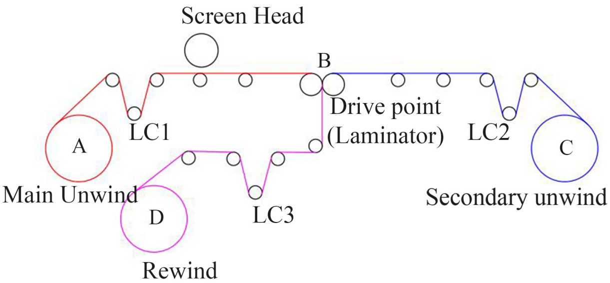


Fig. 3 Film tension control system

The drive control can be visualised using Figure 3. The unwind rollers (A, C) supply the substrate film which is kept at a constant tension using load cells LC1 and LC2, attached to passive rollers and a further load cell LC3after the lamination rollers (B) provides tension reference to the rewind roller (D). To avoid slippage or stretching of the film, a tension of between 0.5 and 3kg is maintained. Currently a tension of 1kg has been determined to be suitable for use with ITO/PET film. Maintaining a consistent central alignment of the film on the rollers is challenging and currently relies on the system finding a natural settling point although this can be wasteful of the film. Forcing alignment has not been implemented as it can induce creases and undesired lateral tension in the film.

The speed of all components is determined by the speed of the laminator rollers which is set and displayed on the human-machine-interface (HMI). Tension of the film is set by the unwind and rewind rollers. When the system is initiating, the rollers run backwards until any slack in the system is removed, at which point normal operation resumes and the unwind rotation speed is fine-tuned to maintain a constant tension. It is important to have the laminator closed for a stable tension because it isolates the operation of each load cell. Running with an open gap would result in a highly unstable system because the load cells would be acting against each other. It is possible to run an open gap but stable operation would rely on the adhesive to bond the film together and multiple panels would need to pass through the laminator to create a stabilised process.

The two laminator rollers have a diameter of 120mm and 20 bit encoders are used throughout the system alongside 500:1 gearheads to ensure a consistent speed throughout the process. A look-up table is loaded each time the system is started and this has default settings which initialise the starting position of each roller and determine the rotational speed of each roller depending on its diameter.

2.3 Screen printed adhesive annulus

The process path initially involves depositing a thin film adhesive sealing annulus using a screen printer. A water-based pressure-sensitive adhesive was used which was chosen for its high temperature resistance and cohesion in addition to maintaining a transparent colourless appearance once dried. A slow film speed allows the water to evaporate between stages, and it is visually apparent when the water has evaporated since the adhesive changes from white (colloidal dispersion state; Fig. 4) to colourless. By the time the film reaches the liquid crystal die coater the adhesive annulus should be tacky to allow for containment of the liquid crystals within it and also allowing for a strong bond when the two plastic films meet at the laminating rollers. It is also important to ensure moisture is removed from the film to avoid contaminating the liquid crystals. This can be aided by using heat or blowing nitrogen over the film.

If an increase in the operational speed is required, it may be necessary to either add an additional step to aid the curing of the water-based adhesive with additional heat, or use a different adhesive material with UV curing properties. The latter is preferable because using heat is not ideal due to undesired thermal stress on the film and the ITO layer.

Figure 4 shows testing of the screen printer depositing an adhesive annulus onto ITO coated PET at a web speed of 200 mm/min. Analysis of this coating using a profilometer (Figure 5) revealed an average thickness of 30 μm. Minor adjustment of the laydown thickness can be achieved by changing the squeegee blade impression.

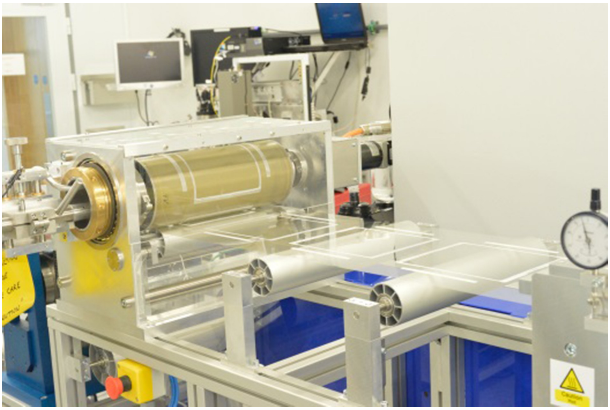


Fig. 4 Rotary screen printed adhesive annulus

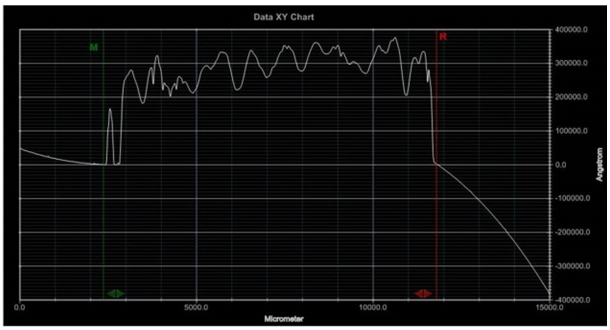


Fig. 5 Surface profile of rotary screen printed adhesive annulus section

A humidifier system has also been incorporated into the screen printer housing to prevent unwanted premature drying of the adhesive, which leads to non-uniformity of coating due to blockage of the screen pores. This problem is exacerbated by the air flow in the clean room environment therefore the screen has been encapsulated in a clear plastic chamber which contains the humidity but allows for viewing of the process.

There are two feeds from the humidifier which lead to the inside and the outside of the screen respectively. The system increases the relative humidity of the printing chamber to 80-90%, which efficiently reduces water evaporation rate and allows the adhesive to maintain good fluidity during the printing process.

2.4 Liquid crystal deposition

To achieve a 10-15μm liquid crystal wet-film deposition, a number of approaches were considered including a spray coat, screen printing, drawdown and die coating . The die-coat approach was chosen because it can provide a uniform square film with minimal interaction with the surrounding adhesive and minimal waste. The quantity of liquid crystal required for the die coater is also significantly less than alternatives such as screen printing and since the display cell spacers are generally mixed into the liquid crystal, the screen or spray approaches are more likely to separate the particles. The die coater also has the important advantage that the temperature of the material can be accurately controlled at all stages of the deposition which is critical in this case due to the elevated deposition temperature. Draw down coating was used during preliminary tests but does not offer the same degree of adjustability and was therefore not chosen for this roll-to-roll system.

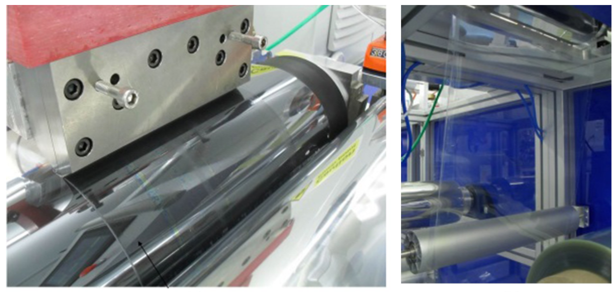
The liquid crystal slot-die coater is triggered by an optical sensor positioned above the film to detect the leading edge of the adhesive annulus, and therefore a 'timer initiated' coating. With this precisely calibrated to the position of the die coater and the film speed, the liquid crystal layer can be accurately deposited within the adhesive with minimal overlap. A slight overlap of the liquid crystal and adhesive is to be expected and this has no apparent effect on the performance of the cell.

The slot-die coater is situated directly above one of the heated laminator rollers. Temperature of the reservoir syringe, die coater and roller can be adjusted individually to allow for maximum control of the liquid crystal deposition. To reduce the coating complexity, the liquid crystal is best dispensed in a low viscous state, preferably in its isotropic phase. This is achieved by heating each component to around 100℃. A pressurised air pulse is used to feed the liquid crystal into the slot-die cavity and once the liquid crystal is in its isotropic phase, a back-pressure is required to prevent unwanted dripping of the mixture. The slot width of the die is determined by mask shim made of a PET film and the thickness of this is balanced with the characteristics of the pressure pulse and LC viscosity to achieve a dispensation of optimal quality and volume. Spacer films in the range of 70~120 μm have been used.

Pulse duration and pressure have a significant impact on the coating quality and it has been found that when the pressure is too high there is a tendency for bubbles to form and if the pressure is too low then the uniformity of the liquid bead beneath the slot is poor. If the pulse duration is too short then the LC may not be dispensed and there is a lack of uniformity. Ideally the pulse duration should continue until the LC material covers the area within the adhesive annulus. A further factor affecting the coating quality is the height of the slot from the moving substrate, known as the coating gap. Ensuring a balance between the coating gap, pulse pressure and time is critical to ensure a quality coating. A long pulse combined with a large coating gap will result in an excess of LC which will be forced out of the edges of the adhesive annulus when it enters the laminator.

The liquid bead in the coating gap is held primarily by shear and capillary forces. Parameters for a stable coating are determined by the capillary number and the ratio of the coating gap to desired wet-film thickness[1]. A lower capillary number is the result of lower viscosity material. When the interfacial tension between the substrate and the coating liquid is regard as constant and the substrate moves at a constant velocity. Since temperature determines the liquid crystal molecular order and therefore viscosity, it also directly affects the critical value of the coating gap. For the slot-die coating of liquid crystals, rheological characterizations of their viscosity change with temperature and shear rate is prerequisite.

Figure 6(a) illustrates the slot-die coater in operation at 100℃ under the stable coating regime, which reveals good uniformity of the wet-film deposition. The lines visible on the film are a result of that particular section of liquid crystal not being sufficiently elevated in temperature to reach its isotropic phase due to the above ambient air flow. The effect to the wet-film thickness can however be neglected. It is important to maintain the level of the slot-die to ensure there is no build-up of liquid crystal at either side of the die-lip. A bead of excess liquid crystal is likely to cause a non-uniform coating. Any non-uniformity that does remain will be removed when the substrate passes through the heated laminator and the liquid crystal is brought back up to isotropic temperature as shown in Figure 6(b).



(a) (b)

Fig. 6 (a) Liquid crystal coating using slot-die (b) Coating after lamination

2.5 Lamination

The two laminating rollers shown in Figure 6 (a) bring the two films together to make a sealed panel. The drive roller is made from chromed steel and is designed to have excellent cylindricity and concentricity. The second roller has a layer of ethylene propylene diene monomer (EPDM) rubber with a shore 65D hardness which allows for a degree of roughness in the film used. The rubber roller is also attached a hydraulic stage enabling lateral movement towards the steel roller to allow the nip gap to be formed. The nip gap is set by adjusting micrometers on either side of the laminator which can compensate for error in the front to back alignment of the rollers.

Figure 7 shows the calibration graphs which were made to correlate the micrometer reading with the actual nip gap across the length of the roller. The temperature across the width of the lamination roller has also been measured to ensure there are no large disparities. As seen in Figure 8, the steel roller is 2.85℃ hotter in the centre than at the edges. This

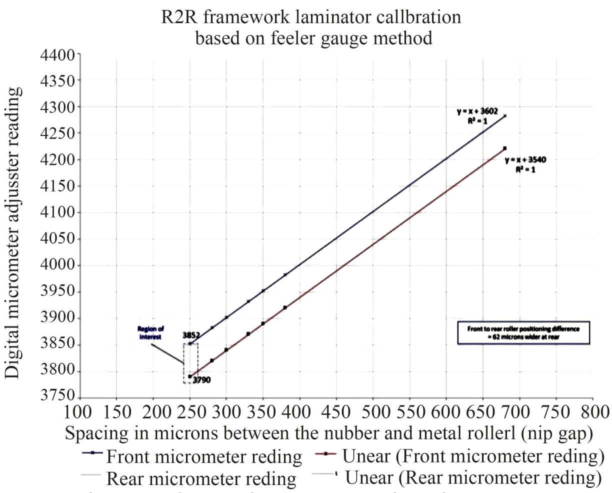


Fig. 7　R2R laminator gap calibration graph

difference is acceptable and will not adversely affect results, however to improve the temperature stability of the die coater and laminator it would be beneficial to cover the area with barrier panelling to limit air flow passing through and providing undesired cooling.

2.6　Rotary die cutter

The final stage of the current system is a rotary die cutter which cuts out 15 cm^2 panels from the laminated PET film as shown in Figure 9. The example shown here consists of two 125 μm thick PET films with liquid crystal in between. There is minimal disturbance to the liquid crystal after the cutting and the edge quality of the cut is very good.

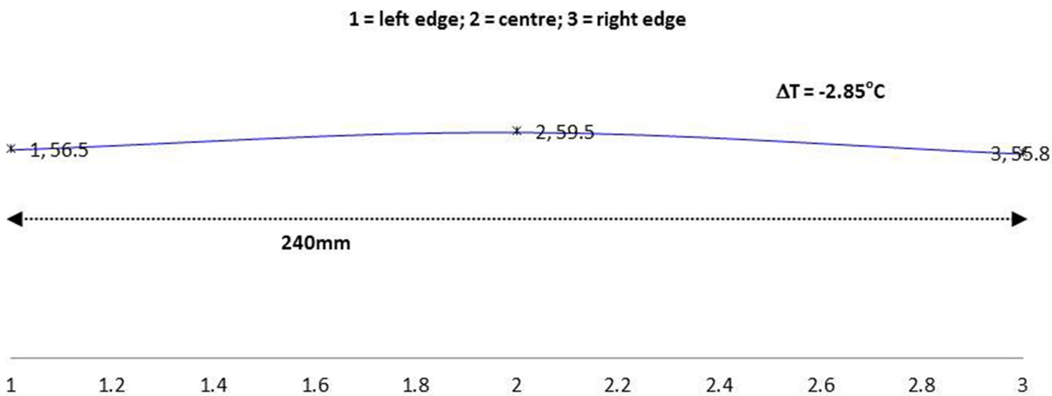


Fig. 8　Temperature distribution across the steel lamination roller at 60℃

Fig. 9　Panels cut out using rotary die cutter

The die cutter is triggered by an optical sensor which detects the leading edge of the adhesive annulus. This is the same approach used to trigger the liquid crystal slot- die coater, however this time both the adhesive annulus and liquid crystal are present on the substrate. Since the liquid crystal tends to overlap the adhesive annulus slightly, the optical sensor struggles to determine exactly where the cut-off region is supposed to be which results in the cut being made in the wrong place. Adding some hysteresis to help the system ignore spurious triggers could be considered here. Another simpler approach is to reposition the sensor to the un-laminated area (. i.e. close to the slot-die sensor) to avoid the influence of the LC layer. Since the annulus size is the same and the tension should remain constant throughout the system, the trigger should also be valid for the die cutter. An additional benefit from the reposition is that it moves the sensor further away from the cutter, eliminating the optical disturbance from film flutters induced by the cutting stress.

3 Conclusions

A dual layer roll-to-roll framework designed for the fabrication of flexible display panels has been realised and demonstrates the potential for industrial scale production. The manufacturing process is simpler and faster than existing techniques which in turn will lower production costs.

The roll-to-roll system has been designed to be versatile, and processes can easily be added and removed depending on the requirements of a particular project. The current system dispenses an adhesive annulus with a screen printer and a slot-die coater subsequently fills the area with liquid crystal before the cell is laminated through heated rollers and cut out using a rotary die cutter. Optical sensors are incorporated to achieve timer initiated slot-die coating and rotary cutting that can be synchronised in speed with the other in-line processing units.

ACKNOWLEDGMENT

This work was supported by Unilever, Dow Corning and RK Print

References

[1] FORREST S R. The path to ubiquitous and low-cost organic electronic appliances on plastic. [J]. Nature, 2004, 428(6986):911-918.

[2] YOU J, DOU L, YOSHIMURA K, et al. A polymer tandem solar cell with 10.6% power conversion efficiency[J]. Nature Communications, 2013, 4(2):66-78.

[3] VÄLIMÄKI M, APILO P, JANSSON E, et al. R2R-printed inverted OPV modules - towards arbitrary patterned designs[J]. Nanoscale, 2015, 7.

[4] CHENG P, BAI H, ZAWACKA N K, et al. Roll - Coated Fabrication of Fullerene - Free Organic Solar Cells with Improved Stability[J]. Advanced Science, 2015, 2.

[5] KREBS F C. All solution roll-to-roll processed polymer solar cells free from indium-tin-oxide and vacuum coating steps[J]. Organic Electronics, 2009, 10(5): 761- 768.

[6] CHA H C, HUANG Y C, HSU F H, et al. Performance improvement of large-area roll-to-roll slot-die-coated inverted polymer solar cell by tailoring electron transport layer [J]. Solar Energy Materials & Solar Cells, 2014:191- 198.

[7] VILKMAN M, HASSINEN T, KERÄNEN M, et al. Fully roll-to-roll processed organic top gate transistors using a printable etchant for bottom electrode patterning[J]. Organic Electronics, 2015, 20:8- 14.

[8] ALLEN M, LEE C, AHN B, et al. R2R gravure and inkjet printed RF resonant tag[J]. Microelectronic Engineering, 2011, 88(11):3293-3299.

[9] TAMAGAKI H, IKARI Y, OHBA N. Roll-to-roll sputter deposition on flexible glass substrates[J]. Surface & Coatings Technology, 2014, 241 (2): 138-141.

[10] PATCHETT E R, WILLIAMS A, DING Z, et al. A high-yield vacuum-evaporation-based R2R-compatible fabrication route for organic electronic circuits[J]. Organic Electronics, 2014, 15(7):1493- 1502.

[11] BAE S, KIM H, LEE Y, et al. Roll-to-roll production of 30-inch graphene films for transparent electrodes[J]. Nature Nanotechnology, 2010, 5(8): 574-578.

[12] ARCILA-VELEZ M R, ZHU J, Childress A, et al. Roll-to-roll synthesis of vertically aligned carbon nanotube electrodes for electrical double layer capacitors[J]. Nano Energy, 2014, 8(9):9- 16.

[13] Guzmán de Villoria, R. H., A. John; Wardle, Brian L. <Continuous high-yield production of vertically aligned cnts on 2d and 3d substreates.pdf>. ACS Nano 5, 19 (2011).

[14] SAKURAI R, OHNO S, KITA S I, et al. 68.2: Color and Flexible Electronic Paper Display using QR-LPD03 Technology [C]. SID Symposium Digest of Technical Papers2006:1922- 1925.

[15] LEE J, SHIN K, LEE C. Analysis of dynamic thermal characteristic of register of roll-to-roll multi-layer printing systems[J]. Robotics and Computer-Integrated Manufacturing, 2015:77- 83.

[16] HASSINEN T, RUOTSALAINEN T, LAAKSO P, et al. Roll-to-roll compatible organic thin film transistor manufacturing technique by printing, lamination, and laser ablation[J]. Thin Solid Films, 2014, 571:212-217.

[17] CHENG-YAO LO, JOHANNA HIITOLA-KEIN01NEN, OLLI-HEIKKI HUTTUNEN, et al. Novel Roll-To-Roll Lift-Off Patterned Active-Matrix Display On Flexible Polymer Substrate[J]. Microelectronic Engineering, 2009, 86(46):979-983.

[18] LO C Y, HUTTUNEN O H, FUJITA H, et al. MEMS-Controlled Paper-Like Transmissive Flexible Display [J]. Journal of Microelectromechanical Systems, 2009(19): 410-418.

[19] KREBS F C. Fabrication and processing of polymer solar cells: A review of printing and coating techniques[J]. Solar Energy Materials & Solar Cells, 2008, 93(4):394-412.

Authors' Biographies

Chris Williamson is a PhD student in the Photonics & Sensors group at Cambridge University Engineering Department. He previously studied for his MEng at Bangor University developing a capacitively coupled organic RFID tag and a high gain valve guitar amplifier which was awarded the most meritorious individual project by an undergraduate in the school of electronic engineering. His current research involves the development of a continuous roll-to-roll manufacturing process for organosiloxane based flexible liquid crystal display panels. Chris is also researching carbon nanotube growth, plasmonics and low voltage field emission.

Email: cjw201@cam.ac.uk

Hsin-Ling Liang received her B. Sc (2004) and M. Sc (2006) in the Department of Engineering and System Science from National Tsing Hua University in Taiwan, later worked as an R&D engineer in the polyimide film manufacturer Taimide Technology. In 2009 she moved to Germany for her doctoral studies as a DAAD fellow and obtained her Dr. rer. nat. (D.Sc.) in 2013 from Johannes Gutenberg University Mainz, Institute of Organic Chemistry with the thesis "Microfluidic-produced liquid crystalline shells". Since 2014 she has joined the Photonics and Sensors Group, Dept. of Engineering, Cambridge University for her postdoctoral research with topics involving dye-doped liquid crystals and the roll-to-roll production of liquid crystal panels.

Email: hll44@cam.ac.uk

Dr Stuart Speakman is a serial inventor and innovator with substantial commercial awareness and extensive high technology research, design, and development experience in thin film science technology and manufacturing. He has over 30 years of experience in thin film technology and is interested in low temperature coating methods for roll-to-plate and roll-to-roll manufacturing as applied to transparent conducting films, thin film transistor circuits, solar energy conversion, resistive random access memory, advanced sensors, and flexible displays. He also has extensive experience in thin coating patterning methods including printing and laser ablation. Stuart is a Fellow of the Institute of Engineering and Technology (FIET) and is a Chartered Engineer (CEng). He is also a director of a company in the field of thin film micropatterning.

Email: sps23@cam.ac.uk

Daping Chu is the Chairman of CAPE (Centre for Advanced Photonics and Electronics) and Head of Photonics and Sensors Group in Cambridge University Engineering Department. Current research includes space light modulation and phase-only holography for displays and imaging as well as optical communications, laminated electro-active foils for solar shading and smart facade, and high frequency tuneable dielectrics for GHz/THz applications.

E-mail: dpc31@cam.ac.uk