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Printed passive matrix addressed electrochromic displays

Peter Andersson Ersman [a,*], Jun Kawahara [a,b,c], Magnus Berggren [b]

[a] Printed Electronics, Acreo Swedish ICT AB, Box 787, SE-60117 Norrköping, Sweden
[b] Organic Electronics, Dept. of Science and Technology, Linköping University, SE-60174 Norrköping, Sweden
[c] R&D Strategy Department, Lintec Corporation, 5-14-42 Nishiki-cho, Warabi, Saitama 3350005, Japan

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ABSTRACT

Flexible displays are attracting considerable attention as a visual interface for applications such as in electronic papers and paper electronics. Passive or active matrix addressing of individual pixels require display elements that include proper signal addressability, which is typically provided by non-linear device characteristics or by incorporating transistors into each pixel. Including such additional devices into each pixel element make manufacturing of flexible displays using adequate printing techniques very hard and complicated. Here, we report all-printed passive matrix addressed electrochromic displays (PMAD), built up from a very robust three-layer architecture, which can be manufactured using standard printing tools. Poly(3,4-ethylenedioxythiophene) doped with poly(styrenesulfonate) (PEDOT:PSS) serves as the conducting and electrochromic pixel electrodes and carbon paste is used as the pixel counter electrodes. These electrodes sandwich self-assembled layers of a polyelectrolyte that are confined to desired pixel areas via surface energy patterning. The particular choice of materials results in a desired current vs. voltage threshold that enables addressability in electronic cross-point matrices. The resulting PMAD operates at less than 3 V, exhibits high colour switch contrast without cross-talk and promises for high-volume and low-cost production of flexible displays using reel-to-reel printing tools on paper or plastic foils.

1. Introduction

Major efforts are currently being devoted to explore and develop new devices and systems for printed electronics applications [1–7]. The theme of this effort aims at providing novel electronic functionalities on flexible substrates such as plastic foils or papers. Flexible display devices are one of the crucial cornerstones of this research and development effort, and a large variety of different flexible display devices and systems have successfully been demonstrated during the last decade, e.g. electrochromic displays, organic light emitting diode displays and electrophoretic displays [8–12]. Since such devices and display systems most often are manufactured in a complex production flow containing one or several vacuum processing steps, there is still a huge technical barrier to carry out an entire manufacturing process using standard sheet-based or roll-to-roll printing, coating and lamination techniques.

Electrochromic (EC) active matrix addressed displays (AMAD) have been explored for various low-end display applications, in particular for areas in which the requirements on e.g. switching time and pixel resolution are a bit relaxed. EC-AMADs, which are built up from pixels including a display element and an addressing transistor, have been demonstrated on either paper or plastic substrates [12–14]. Even though the very same materials have successfully been utilized as the active material in both display elements and transistors, EC-AMADs still require a fairly large number of printed layers, thus ruling out simple manufacturing and low cost.

* Corresponding author. Tel.: +46 11 202507.
E-mail address: peter.andersson.ersman@acreo.se (P. Andersson Ersman).

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In passive matrix addressed displays (PMAD) addressing transistors are not utilized to provide addressability for the display element. In PMAD configuration, the system complexity is then much lower which enables a relatively much simpler manufacturing scheme. However, one particular drawback of PMADs is that they typically suffer from cross-talk effects, i.e. the applied voltage aiming to update one specific pixel, at the intersection of a certain row and column, also affects and causes coloration of neighbouring non-addressed pixels [15]. There are various ways to circumvent such cross-talk effects in PMADs, for example by combining each pixel with a diode exhibiting rectifying and strong non-linear current vs. voltage (*I–V*) characteristics [16], but yet again, additional components implies an increased number of processing steps.

Here, we have developed EC pixels exhibiting non-linear coloration vs. addressing voltage characteristics with a threshold voltage at around ±1 V. The EC pixel exhibits good bi-stability as the addressing voltage is decoupled. The electrode and electrolyte materials were deposited by screen printing and wire bar coating, respectively, on top of flexible plastic substrates and the number of included layers was kept at a minimum; an electrically conducting carbon paste, an ionically conducting polyelectrolyte and an electronically conducting electrochromic polymer served as the counter electrodes, the electrolyte and the pixel electrodes, respectively. This very simple three-layer device architecture was enough to define an entire EC-PMAD containing up to 7 × 128 EC pixels. This EC-PMAD, based on the robust and simple device architecture shown in Fig. 1, is promising as the display interface in all-printed electronic systems in applications such as distributed diagnosis, home healthcare or sensor platforms monitoring the status of perishable goods in logistic chains.

2. Materials and methods

2.1. Materials

Transparent polyethylene terephthalate (PET, Polifoil Bias) film was purchased from Policrom Screen and was used as the solid substrate carrying the display components. As a top electrode, PET film with pre-coated PEDOT:PSS (Orgacon EL-350) was purchased from AGFA-Gevaert. This product was also used as the counter electrodes for the reference samples. Conducting carbon paste (7102) for screen printing was purchased from DuPont and printed onto the PET substrate by using a 120-34 nylon screen mesh (120 threads/cm, thread diameter 34 μm), followed by drying process at 120 °C for 5 min. An aqueous solution of poly(diallyl dimethyl ammonium chloride) (PDADMAC), purchased from Sigma–Aldrich, was used as the water-based polyelectrolyte. To obtain a white opaque electrolyte, 10 wt% of TiO_2 powder (KRONOS 2300 purchased from KRONOS) was added into the polyelectrolyte solution and mixed carefully before use. The solution of pH colour indicator (Universal indicator solution 36,828, pH 4–10) was purchased from Riedel-de-Haën GmbH.

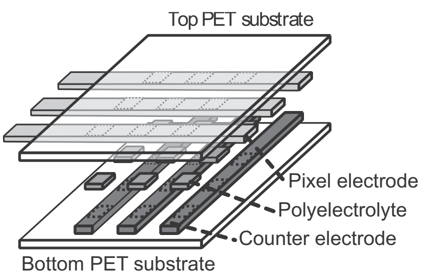

Fig. 1. An illustration showing the simple architecture of a 3 × 3 EC-PMAD consisting of 9 EC pixels.

2.2. Electrical characterization of EC pixels

The PEDOT:PSS layer on the Orgacon film was cut and patterned into an area of 35 × 35 mm^2 by using a knife plotter tool, and the square-shaped pattern was then used as the pixel electrode. A 35 × 35 mm^2 square of conducting carbon was screen printed onto a PET film and used as the counter electrode. At one corner of each electrode, a 5 × 5 mm^2 active area was defined by attaching a spacer consisting of an adhesive plastic film having an area of 20 × 20 mm^2 with a 5 × 5 mm^2 cavity. The white and opaque electrolyte was deposited manually onto each electrode and dried into a semi-solidified state for 1 min at 60 °C. After drying, each set consisting of one pixel electrode and one counter electrode was laminated to complete one EC pixel cell.

2.3. I–V measurement setup in ambient atmosphere

Each EC pixel device was biased by using an Agilent 4155B Semiconductor Parameter Analyser, and the electric current between the counter and the pixel electrodes was recorded as a function of the applied potential. The voltage was swept in the range of ±2.5 V at an increment of 10 mV per sample and the time between two samples was set to 20 ms.

2.4. Measurement setup to determine the switching behaviour of EC pixels

EC pixels having an area of 1.5 × 1.5 mm^2 were manufactured according to the description above, but they were instead used to observe the colour switching behaviour as a function of the applied potential. The measurement was performed by using a laser diode in conjunction with a photodiode [17]. The display was irradiated by a laser diode peaking at 650 nm, a wavelength that matches the absorption peak of the reduced state of PEDOT:PSS, and the scattered light was detected by a photodiode (S1337-66 from Hamamatsu, 5.8 × 5.8 mm^2 active area) and the photocurrent was recorded using a Keithley 2400 SourceMeter.

2.5. Investigation of the electrochemical capacitor

Two rectangles (20 × 5 mm^2) of conducting carbon paste 7102 were stencil printed onto a PET substrate. A polyelectrolyte consisting of PDADMAC was mixed with