Intelligent Packaging with Inkjet-Printed Electrochromic Paper Display – A Passive Display Infotag

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Abstract

In this paper, we study the electronic performance of the inkjet-printed electrochromic (EC) display which uses Poly (3,4-ethylenedioxythiophene) (PEDOT) doped with poly (styrenesulfonate) (PSS) as the active material, and extract its equivalent RC model. Results show that by charging PEDOT:PSS with 1.8V for averagely 10s, it can be switched from transparent (oxidation state) to blue (reduced state) and keeps the color for an average of 300s in the absence of energy supply, consuming much lower power than other flexible display technologies. However, it suffers from significant crosstalk effects in passive-matrix addressing and from performance variation as sample changes or time goes on. Based on the results, we design a programmable digital display driver with two different operation modes, and analyze the feasibility to integrate such display function in passive intelligent packaging systems. System simulation results prove it as a promising solution from evaluation of power budget and driving ability with printed interconnections and offchip conductors.

Introduction

In the future internet-of-things, common products can have the internet connectivity as today's numerous electronic gadgets by integrating their packages with a low-power easy-integrated wireless "tag", and displaying the required information such as position, stock and transporting status. However, there are three main challenges in realizing such a system – printed display co-design, low power consumption design, and maximizing system intelligence under the foregoing limits. Most of the current electronic paper display which resembles normal paper in its appearance and light-reflecting characteristic demands very high voltage over 10V, impossible to meet the low power specification and integrate display functions in intelligent packaging at object-level. Inkjet-printed EC display, however, offers a possibility to solve the three challenges thanks to its low active voltage.

This paper investigates the electronic properties of the inkjet-printed EC display and analyzes its feasibility to be integrated in a passive low power radio tag as an intelligent packaging. The remaining of this paper is organized as follows: First, the principle of inkjet-printed EC display is introduced. Secondly, an equivalent electronic circuit model of EC display is extracted based on a series of performance measurements. Thirdly, process variation and crosstalk effects of EC display are measured and discussed. Fourthly, a specific display driver is designed based on the foregoing results and the three challenges. Finally, feasibility and performance of the proposed display and display driver are discussed taking printed interconnection and connection into consideration when integrated into the entire Infotag system.

Principle of Inkjet-printed EC Display

Infotag selects EC display from Acreo Paper Display due to its printability, bi-stability and low switching voltage.

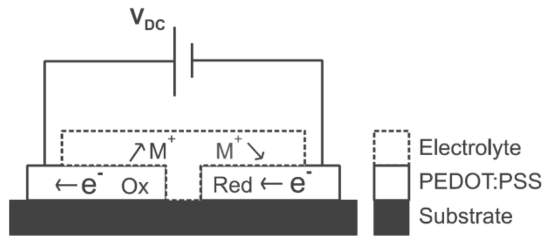

***Figure 1**. The architecture of a lateral EC display cell. In the positive electrode PEDOT becomes oxidized, while in the negative electrode PEDOT is switched to the dark blue colored reduced state [1]*

In this technology the display element consists of an active electrode (pixel) and a counter electrode, both covered by a solid electrolyte as shown in figure 1. The electrodes which are made from PEDOT-PSS serve both as electrochromic material and electrical conductor, enabling the simultaneous printing during integration [1]. Compared to other bi-stable display technologies on flexible substrate – OLED, Electro-phoretic display, Electro-wetting display and Cholesteric-LCD [2-6], the switching voltage of EC can be as low as 1.5V, satisfactorily compatible with CMOS operating voltage. Table 1 compares the basic parameters of EC display with other electronic paper display technologies.

Table 1. Electronic paper display comparison

Technology	Active Voltage (V)	Response Time (ms)	Contrast Ratio (%)
Electrophoretic Microencapsule	15	50	10
Electrophoretic Air-Gap	70	0.2	
Electrowetting/ Electrofluidic	20-60	3-10	>10
Flexible OLED/ Polymer LED	NA*	<1	100
Ch-LCD	>40	1750	25
Electrochromic	1-3.3	<16000	>15

*OLED is supplied by current at tens of micro-ampere.

To reduce the pin numbers interfacing IC and display for heterogeneous system integration, the display driver is mandatory to use matrix-addressing method. Because active-matrix addressing requires transistors such as TFT alongside each pixel, which is not mature enough for current inkjet-printed EC display, the passive matrix-addressing is pre-defined for the display driver.

Electronic Circuit Model Extraction

Extraction is made up of two steps: step 1 defines equivalent RC structure, and step 2 measures the equivalent RC values. The tested display samples are two displays, each with 8 columns and 2 grounds. Step 1 is made up of one assumption and three measurements.

First, because the display is switched to reduced state by electronic energy and can stay in the reduced state with the absence of power supply for a limited retention period, the display is assumed to resemble the energy storage effect of a capacitor (C) paralleled by a discharge resistor (Rp).

Secondly, the DC performance is measured by driving the display with a constant voltage source. The measured currents keep decreases yet will never decrease to zero (more accurately, instrument current below nano-ampere). This indicates that the display has a current path consisting of only resistance in both the oxidized state and the reduced state.

Thirdly, the frequency response is measured by applying a square-wave voltage source with different frequencies and duty cycles under the same voltage amplitude. Results show that the display's switching state is sensitivity to the driving frequency and duty cycle. This not only verifies the assumption of capacitance model, but also indicates a resistance (Rs) serial to it, combining a low pass filter structure as a whole.

Fourthly, the diode performance is measured by reversing the electrodes connection with supply, and repeating the previous experiments. Results show no obvious difference from the previous ones, indicating that EC display has no diode model as exists in OLED displays.

In summary the EC display shows a circuit model in figure 2.

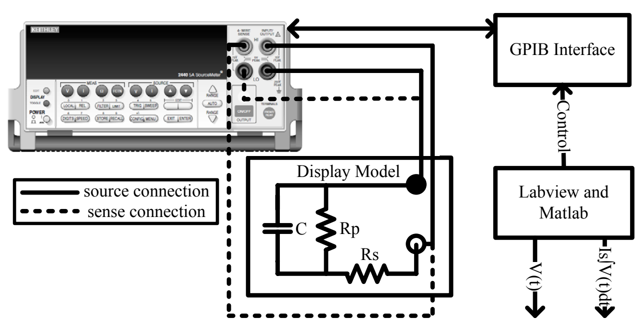

***Figure 2**. Circuit model of EC display and test setup for switching energy*

In step 2, the RC values based on the defined model structure can be simultaneously extracted by one measurement setup. Conventional method is to use an LCR meter; however this equivalent capacitance changes significantly with different voltages and frequencies, and responses very slowly to common LCR meters. So it is hard to extract the equivalent C and in turn the R values by common LCR meter.

Instead, the non-constant RC values are measured by charging a fully-discharged display with a constant current source, and turning off the current source when it starts to enter the reduced state. Voltages are measured and recorded at the sample rate from 10ms to 20ms controlled by Labview from National. Keithley-2440 is used as both the current source and the voltage meter. Results are demonstrated in figure 3 by the test setup in figure 2. Theoretically, the voltage should rise to a DC offset the moment the Isource is on (as the dotted simulation line shows) for the proposed RC structure; the slow rising curve in the measured results reflects non-constant values of Rs. Similarly, the non-constant C values shifts the voltage from a simulated linear rise curve during the charging phase. However, the average values of C and Rs can be obtained and useful as long as the results are only targeted as the instruction for display driver design described in the next section.

Equivalent RC values are deduced by the capacitance IV law (1.1), Ohm's Law V0=Is×Rs, and an extrapolation for V0 from tested V1 and V2 as described in (1.2).

$$V2-V1/t2-t1 = Is/C \quad (1.1)$$

$$(V2-V1) / (t2-t1) = (V2-V0) / (t2-t0) \quad (1.2)$$

Rp can be directly extracted by the discharging period based on the well-understanding RC discharging equation. Area-normalized values are listed in table 2. Inputting the values in ADS outcomes the simulation results relatively conform to the measurement results as shown in figure 3.

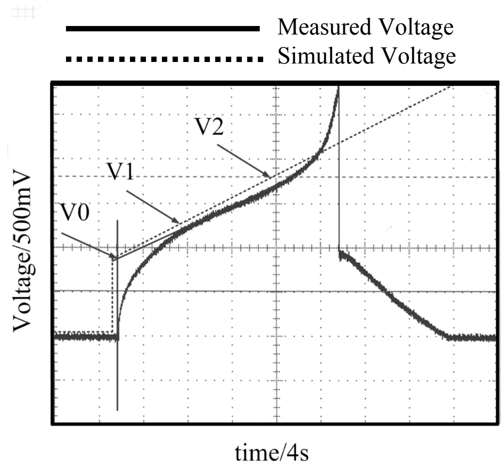

***Figure 3**. Measured and simulated voltage by a 2uA DC current source*

Furthermore, the switching energy (E_th) and voltage (V_th) are also measured because they are among the most important factors that evaluate display's feasibility of integration with the passive Infotag. The measurement setup is the same with RC model extraction in step 2, only by changing the current source to voltage source, and the voltage meter to current meter. The measured currents are recorded for integral calculation in Matlab. Corresponding switching voltage (V_th) can be calculated by $E=0.5 \times C \times V^2$. The current result is shown in figure 4; the switching energy and voltage results are listed in table 2. The calculated voltage conforms to measured voltages that switch the display to reduced state.

Table 2. Electronic Model of EC Display

Rs	~ 150Kohm/cm²
C	~ 15uF/ cm²
Rp	~ 3Mohm/cm²
E_th	~150uJ/cm²
V_th	~2V

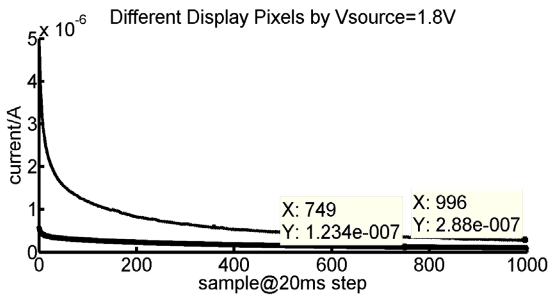

***Figure 4**. Measured currents of two display pixels through the charging phase*

Process Variation and Crosstalk Measurement

In order to study the process variation of EC display, two display samples each with 8 different segments are measured over a 3-months period. Results shows that the switching energy does not change much, but the refresh time varies from 1s to 15s and retention time from 180s to 560s. The measured results illustrate that the operating parameters suffer significant variations owing to printing and manufacturing process from sample to sample and from time to time. So, the timing circuit in display driver must provide the programmable refresh time and retention time. Meanwhile, the minimum retention time and the maximum refresh time results in the highest possible power consumption around 50uW according to equation (2).

$$P\_disp = (t_{refresh} + t_{retention}) \times E\_th \quad (2)$$

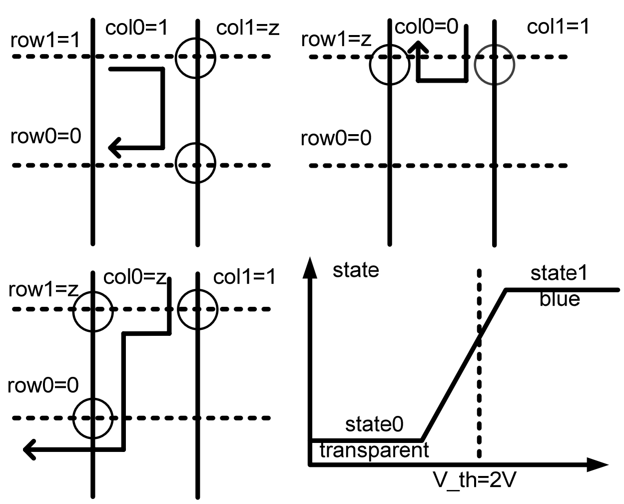

***Figure 5**. Threshold voltage of display state switching and crosstalk effect in 3 passive matrix-addressing methods*

Crosstalk effect of EC display is also measured. Crosstalk effect describes the phenomena that when one pixel is "lighted", a certain number of other pixels which are not intended to "light" will also light. This is specific to passive matrix-addressing because there is always a voltage drop across every pixel as long as one pixel is connected to the supply pair. Based on the switching energy experiments in the previous section, the threshold voltage driving PEDOT to the reduced state is not sharp enough, especially around the CMOS supply voltage levels (1.0V to 1.8V), resulting in significant crosstalk effect in all the three passive-matrix addressing methods as illustrated in figure 5.

Display Driver Design

Based on the electronic model as well as process variation and crosstalk measurements in the foregoing sections, a specific digital driver is designed.

First, the display requires active voltage lower than 1.8V, and the equivalent R is at tens of MΩ, comparable to the high-z impedance of a standard IC (integrated circuit) I/O driver, so a digital display driver is selected, saving not only the complexity and power consumption from otherwise required analog circuits but also the signal integrity problem owing to printed conductor's limited conductance.

Secondly, because of the equivalent C with a parallel Rp, the display must be "cleared" every time before showing a new data to remove the values sustained from the previous data, the "clearing" is done by reversely-connecting the supply voltages to all the column-row pairs (row to Vsupply and column to ground). And because the comparable RC charging and discharging time, the clearing time is comparable with the refresh period.

This model also enables the display to operate in two modes – continuous mode and onoff mode. In continuous mode, the display driver remains in refresh state and sustaining supply voltage to display, while in onoff mode the display driver circulates between refresh state for a refresh period ($t_{refresh}$) and idle state for a retention period ($t_{retention}$). The retention time for onoff mode is programmable according to the measured variation bounds ranging from 120s to 600s with typical value of 300s based on the extracted discharging resistance and capacitance. The benefits of onoff mode is that it saves the sustain current at micro-ampere level as measured in figure 4 as well as the clock generation power during the retention time. In both continuous and onoff modes, the refresh time is programmable according to the measured variation bounds ranging from 1s to 20s with typical value of 10s.

Thirdly, according to the results in figure 5, however the pixels are arranged, there is a crosstalk voltage around Vsuppy/2. Based on the averaging switching voltage of 2V and standard CMOS supply choices, a supply voltage of 1.8V is selected.

Fourthly, because the display shows a low pass filter effect, frequency of the driving voltage must be lower than a certain value; and because the driving frequency is generated from relative high frequent global clock, the lower it is the higher power consumption of the clock generating circuit.

Therefore, the final display driver is a digital driver with standard IO, outputting a square wave with 1.8V supply voltage, 4Hz frequency, 50% duty cycle, programmable clear, refresh and retention periods.

System Architecture and Result Discussion

The designed display driver with the EC display is evaluated as an integrated part of Infotag. The system architecture of Infotag consists of an UHF antenna, an inkjet-printed EC display, an UWB antenna, and a battery-less IC including a power scavenging and management unit, a narrowband UHF receiver, an impulse UWB transmitter and a digital baseband with the display driver. Area-consuming off-chip display is printed and flexible to realize co-production with common packages. For intelligent packaging application, UWB transmission replaces UHF in uplink communication to take its advantage of high data rate at 10Mbps to 100Mbps and ultra-short pulses for indoor position [7].

Based on this build-up architecture, the power consumption of IC part can be simulated and is listed in table 3, with a summary around 20uW @ 10M UWB data rate. In this part, display energy is $E_d \approx 150uJ/cm^2$, UWB energy is $E_u \approx 9.2pJ/pulse$ with $f_{data\text{-}rate} \approx 10MHz$; efficiency of UHF antenna and power management unit in the IC tag is evaluated around 30%, ρ_d is display duty cycle. According to Friis Equation (3.1) and equation (3.2-3.3), the power budget and operation distance can be reached considering free space propagation loss and assuming 0dB receiving antenna. The evaluated distance over 10 meters indicates that EC display is suitable to be integrated Infotag from top-level view.

$$P_{in} = P_{source}(\lambda/4\pi d)^2, \quad (3.1)$$

$$P_{in} > P_{out}/\rho_{rec}, \ (\rho_{rec}\text{: rectifier efficiency}) \quad (3.2)$$

$$P_{out} = \rho_d \times P_d + \rho_u \times P_u, \ (\rho_u\text{: UWB efficiency})$$

$$= (t_{refresh} + t_{retention}) \times E_d + (t_{pulse}/t_{data\text{-}rate}) \times E_u \times f_{data\text{-}rate} + P_{other} \quad (3.3)$$

Table 3. Power consumption of functional blocks

Functional blocks	Power Consumption
Power Management Unit	0.36uW
Detector and Decoder	0.24uW
CLK generator	12uW
UWB Transmitter (E_u)	0.92uW (average)
Display Driver	2uW
Display (E_d)	~150uJ/cm²
other baseband blocks	<10uW

Besides the power budget analysis, when the evaluation of display function is concerned, the inkjet-printed EC display has significant crosstalk effect because any small current leakage can be accumulated to surpass the material's state-switching energy after long enough time. Current solution of a specific-selected square wave is effective yet not satisfactory enough for long-time application or random-sample application. Therefore either an active-matrix display should be manufactured or the display should be improved in the switching energy for more applicable usage in the future.

For the display's interconnection with IC part, the display shows serial resistance at hundreds of kilo-ohm. According to [8] the influence of ACF interconnection can be safely ignored, and further according to [9] the printed nano-silver conductors has very poor conductivity but it can still be reduced to below 100 ohm by a special tapered microstrip line (TML). Therefore, the interconnection of printed conductors and ACF shows equivalent resistance much smaller than that of printed display, and thus their side effects to printed EC display performance can be neglected.

As a summary, the EC display and the programmable digital display driver with two operation modes can realize the basic display function in Infotag, the passive intelligent packaging system. Better realization, however, demands an improvement in crosstalk effect of EC display.

Conclusion

This paper studies the electronic properties of the inkjet-printed EC display, and proposes a programmable digital display driver. How the display driver and EC display integrate in the whole system architecture of Infotag is discussed from the three challenges – seamless integration of circuit with inkjet-printed components, low power consumption design, and maximizing system intelligence. In conclusion, EC printed display and the digital driver makes it possible to realize an intelligent packaging exemplified as Infotag.

References

[1] P. Andersson, R. Forchheimer, "Printable All-Organic Electrochromic Active-Matrix Displays", Jour. Advanced Functional Materials, 17, 16 (2007).

[2] T. Bert, G. Van Steenberge, Passive Matrix Addressing of Electrophoretic Image Display (Eurodisplay, Nice, France, 2002) pg. 251.

[3] S. Venugopal, R. Shringarpure, Integrated a-Si: H Source Drivers for Electrophoretic Displays on Flexible Plastic Substrates Flexible, Proc. Flexible Electronics and Displays Conference and Exhibition, pg. 1. (2008).

[4] I. Hsieh, L. Chen, H. Chen, Low Driving Voltage of Electrowetting Display on Flexible Substrate, Proc. Flexible Electronics and Displays Conference and Exhibition, pg. 1. (2008).

[5] S. Tokito, D. Kumaki, 6 Inch-Flexible AM-OLED Moving Image Display, Proc. Flexible Electronics and Displays Conference and Exhibition, pg. 1. (2009).

[6] Deng-Ke Yang, "Flexible Bistable Cholesteric Reflective Displays," Jour. Display Technology, 2, 1 (2006).

[7] M. Baghaei-Nejad, D.S. Mendoza, A Remote-Powered RFID Tag with 10Mb/S UWB Uplink And −18.5dbm Sensitivity UHF Downlink in 0.18µm CMOS, Solid-State Circuits Conference - Digest of Technical Papers, pg.198. (2009).

[8] L. Xie, J. Shen, Co-design of Flip Chip Interconnection with Anisotropic Conductive Adhesives And Inkjet-Printed Circuits for Paper-Based RFID Tags, Proc. Electronic Components and Technology Conference (ECTC), pg.1752. (2011).

[9] B. Shao, Q. Chen, An Ultra-Low-Cost RFID Tag with 1.67 Gbps Data Rate by Ink-jet Printing on Paper Substrate, Proc. Solid State Circuits Conference (A-SSCC), pg.1. (2010).

Author Biography

Jue Shen received her bachelor's Degree in Fudan Univ. Shanghai China, and her Double-master's Degree in KTH (Royal Institute of Technology) Sweden and Fudan Univ. During her study, she has also interned in Intel for 1 year. She has been doing her Ph.D research in KTH iPack Center from 2009 to present, with interest in intelligent packaging for internet-of-things and ambient intelligence based on printed electronics and low power microelectronic design.