20.1: Microcup® Active and Passive Matrix Electrophoretic Displays by Roll-to-Roll Manufacturing Processes

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Abstract

Rolls of flexible electrophoretic panels have been prepared by the SiPix roll-to-roll manufacturing process based on novel Microcup® and top-sealing technologies. The resultant Microcup® passive matrix electrophoretic displays (PMEPDs) and a-Si TFT active matrix electrophoretic displays (AMEPDs) have shown outstanding contrast ratio, switching rate, image bistability, threshold characteristics, grayscale capability, operation temperature latitude, and physicomechanical properties.

1. Introduction

High performance, format flexible Microcup® passive matrix electrophoretic displays (PMEPDs) having threshold voltages ranging from 5-50V have been demonstrated recently[1,2]. Ultra thin and ultra lightweight plastic electrophoretic displays (EPDs) may be prepared roll-to-roll on a web at very high speed and low cost.

The inherent threshold characteristics of the Microcup® PMEPDs has been achieved by optimizing the particle-particle, particle-sealing, and particle-Microcup® interactions without the need of complex electrode structure[3,4] or magnetic particles/electrodes[5]. No tradeoff in colloidal and shelf life stability was observed.

In this paper, the barrier properties of the top-sealing layer, the gray scale capability, edge-sharpness and operation temperature latitude of typical Microcup® EPDs will be discussed. Electro-optical responses of the 1st generation Microcup® PMEPDs and AMEPDs equipped with a conventional a-Si TFT back plane will also be reported.

2. Microcup® EPDs and Roll-to-Roll Manufacturing Processes

As shown in the schematic Figure 1, an electrophoretic fluid comprising charged pigment (TiO_2)-containing microparticles dispersed in a colored dielectric solvent is enclosed and seamlessly top-sealed in the Microcups®. Color rendition may be achieved either by using a color filter or by sequentially filling and sealing R,G, B, electrophoretic fluids in the Microcups®.

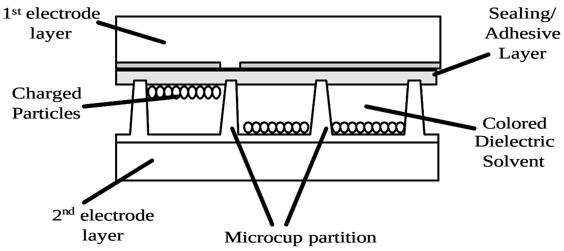

Figure 1 Schematic cross-section of a Microcup® EPD. Each Microcup® is isolated and seamlessly top-sealed. The 1st electrode layer may be a TFT back plane.

2.1 The Electrophoretic Composition

The proprietary charged pigment-containing microparticles are submicron in size with a narrow size distribution. They are density-matched very closely to that of the dielectric solvent. Excellent colloidal stability has been observed even after the electrophoretic composition was centrifuged at 1000G for more than 30 minutes.

2.2. The Microcups®

Depending on the application, typical dimension of the Microcup® may vary in the range of 50-180 um (width, length, or diameter) x 12-40 um (height) x 8-25 um (partition width). The Microcup® array may be prepared by a lithographic or embossing process. The Microcups® are subsequently filled with the electrophoretic fluid, top-sealed with the SiPix 1-pass or 2-pass sealing process[1,2,6], and finally laminated with a second electrode layer or a temporary release liner. An optical photograph of the cross-section of a top-sealed square Microcup® array with a 4-5 um sealing/adhesive layer is shown in Figure 2.

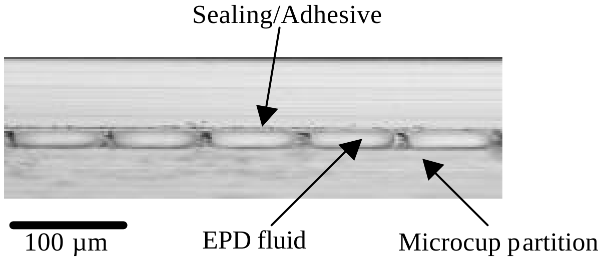

Figure 2 Optical photograph of cross-section of a typical Sipix top-sealed Microcup® array prepared by a roll-to-roll process.

2.3 Barrier Properties of the Sealing Layer

For AMEPDs and direct drive EPDs, the Microcups® may be formed on a non-patterned electrode layer, top-sealed and laminated onto a release layer. The resultant sandwiched EPD film may be converted by customers to a module by peeling off the release and laminating the top-sealed Microcups® onto a patterned electrode layer such as an a-Si TFT back plane. To preserve the dielectric solvent in the top-sealed Microcup® during shipping and storage, a sealing layer with satisfactory barrier properties is required. Figure 3 shows the TGA thermographs of a typical dielectric solvent in open and as-sealed Microcup® arrays without a protecting layer above the sealing layer. The onset temperature of solvent evaporation (T_{onset}) in an open Microcup® array is about 33°C (Curve a). The same solvent was top-sealed in the Microcups® and the thickness of the sealing layer was determined by cross-sectional SEM of the sealed Microcups®. As it can be seen clearly that the T_{onset} was significantly increased to 179°C, 186°C, and 197°C when the thickness of the sealing layer is 1-2 um, 3-4 um, and 4-5 um, respectively. A seamless sealing layer with good film integrity is evident from the high T_{onset} of the top-sealed samples.

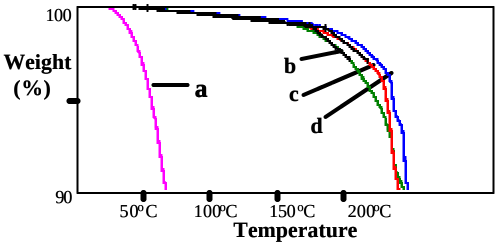

Figure 3 TGA thermographs of a typical dielectric solvent in open Microcups® (Curve a; T_{onset}=33°C) and in a top-sealed Microcup® array: Thickness of the sealing layer: 1-2 um (Curve b; T_{onset}=179°C), 3-4 um (Curve c, T_{onset}= 187°C), and 4-5 um (Curve d, T_{onset} =192°C). All the TGA were measured without a top substrate laminated onto the top-sealed Microcups®.

The activation energy of solvent permeation through the top-sealing layer was estimated by the TGA heating rate method to be about 26 Kcal/mol. The high T_{onset} together with the high barrier activation energy assure a long process green time of the as-sealed Microcups® since the dielectric solvent may be well preserved before the subsequent lamination step.

2.4 Edge Sharpness of Microcup® EPDs

Figure 4 shows the optical photograph of a typical Microcup® EPD driven with a sharp-edge electrode pattern. It is evident that the electrophoretic composition in Microcups® can be partially addressed to exhibit an edge-sharpness significantly finer than the dimension of the Microcups®.

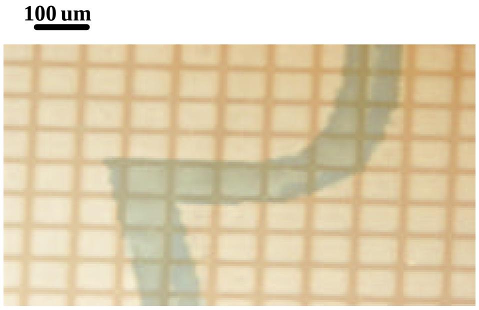

Figure 4 Optical photograph of a Microcup® EPD showing partially addressed Microcup® using a sharp-edge electrode pattern.

2.5 Operation Temperature Latitude

The switching rate of an EPD is inversely proportional to the viscosity of the electrophoretic fluid. As temperature decreases, the switching rate typically decreases significantly since the viscosity of a colloidal dispersion generally increases with decreasing temperature. The temperature effect is particularly significant if a phase transition or a critical flocculation phenomenon involved. SiPix's unique filling and top-sealing processes allow the electrophoretic composition be optimized independently from the surrounding partition walls and sealing layer. The excellent barrier properties of the top-sealing layer further allow the use of a low boiling solvent of low viscosity which is relatively insensitive to the change of temperature in the range of interest. Figure 5 shows the effect of operation temperature on the optical response of a typical Microcup® EPD. The arrows represent the sequence of the heating and cooling cycle. It is evident that the optical response of the Microcup® EPD remains almost the same in the whole temperature range investigated. The temperature latitude may be further extended to -20°C with or without a thermal compensation mechanism.

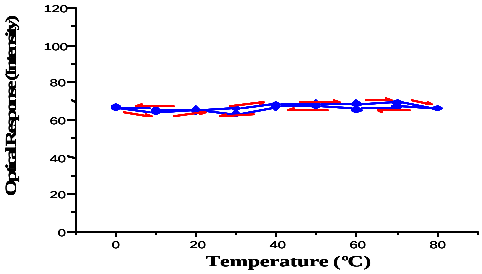

Figure 5 Effect of heating and cooling cycle on the electro-optical response of a typical Microcup® EPD.

3. Microcup® AMEPDs

Microcapsule AMEPDs[7,8] and in-plane switching AMEPDs[9] have been reported recently. In comparison, the SiPix Microcup® structure and the roll-to-roll manufacturing processes provides an alternative solution with significantly improvements in cost, process latitude, and performance. For example, a jumbo roll release liner/top-sealed Microcup®/ITO/PET sandwiched film was cut to desirable format. The release liner was peeled off, and the top-sealed Microcup® film was laminated onto a commercially available 3.5" color QVGA reflective a-Si TFT back plane. To simplify the driving, all three R,G, B sub-pixels were connected together to form 223.5 um x 223.5 um monochrome pixels. A conventional STN LCD driver IC was used for the source driving, a TFT gate driver IC was used for gate driving, and a FPGA was used to provide the timing control for both binary and grayscale modes. Figure 6 shows the electro-optical response of the resultant a-Si TFT Microcup® AMEPD prototype measured according to the procedure described in the previous paper[2]. The contrast ratio, frame rate, and image bistability driven at about ±10 volts are ≥8, ≤0.5 sec, and ≥24 hours, respectively.

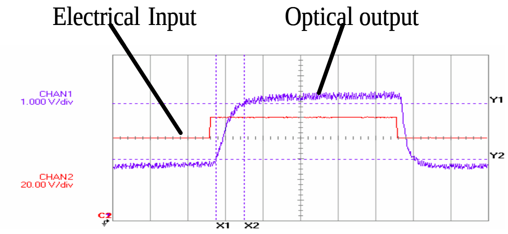

Figure 6 Electro-optical response curves of the 1st generation a-Si TFT Microcup® AMEPD driven at +10 V. t_{on} = about 400 msec.

4. Microcup® PMEPDs

A PMEPD driven by traditional column and row electrodes has been generally considered a major technical challenge. The threshold characteristics needed to suppress the undesirable cross effects among adjacent pixels during multiplexing driving does not exist in most electrophoretic systems. An electrophoretic fluid having inherent threshold characteristics has been reported[10], however, with undesirable tradeoffs in response time, operation voltage, brightness, image uniformity, and display longevity.

In contrast, by optimizing the particle-particle, particle-sealing layer, and particle-Microcup® interactions, satisfactory threshold characteristics have been demonstrated without the tradeoffs. High performance Microcup® PMEPDs have been prepared at high throughput by the SiPix roll-to-roll process using column and row patterned ITO/PET films. Figure 7A showed the typical electro-optical response curve of a Microcup® PMEPD as a function of driving voltage from 0~40 volts. Saturated optical signal could be reached at $\geq$30 volts with a t_{on} of about 60 msec, but no signal was detected at all at $\leq$10 volts. Figure 7B shows that the PMEPD exhibits a contrast ratio of about 10 at $\geq$25 volts and a threshold voltage of about 10 volts. Excellent image uniformity and shelf-life stability were also observed.

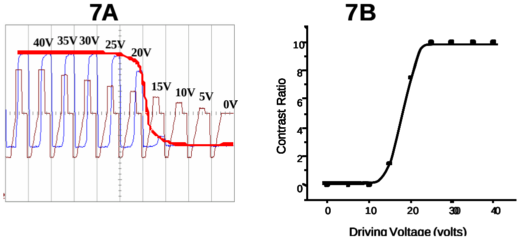

Figure 7 Electro-optical response (7A) and contrast ratio-voltage (7B) curves of the 1st generation Microcup® PMEPD.

The SiPix proprietary pigment-containing microparticles and the unique Microcup® structure and top-sealing process appear to provide extremely wide formulation and process windows for the optimization of all the above-mentioned interactions and in turn enable a high performance PMEPD. A 20x30 lines PMEPD prototype with a frame rate of $\leq$ 2 sec and a contrast ratio of about 10 driven at 30 volts has been demonstrated recently.

5. Gray Scale of Microcup® EPDs

A microcapsule type of AMEPD capable of four-level grayscales has been demonstrated recently by an area modulation mechanism[7] at the expense of pixel resolution. In contrast, Microcup® EPDs are capable of a significantly higher gray scale without the tradeoff in pixel resolution. As it is evident from Figure 8, except the initial few "wake-up" pulses, the optical response of each electric pulse is bistable and additive until a subsequent pulse is given.

. Because of the superior bistability of mid-tone image of Microcup® EPDs, gray scale rendition may be achieved by the pulse width (Figure 9A) or pulse count (Figure 9B) modulation mechanism, or their combination. Six grayscale levels are shown in Figure 9, although more than 10 gray levels has demonstrated by either modulation mechanism. Since the resolution of a typical Microcup® is quite high, 50-180 um or 120-500 cup-per-inch, as compared to the pixel resolution of a typical LCD, high quality image may be achieved by further combining the area modulation mechanism with the pulse count and/or width modulation mechanisms.

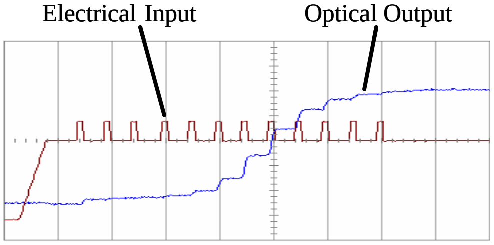

Figure 8 Additive gray scale rendition showing mid-tone image bistability of a Microcup® EPD.

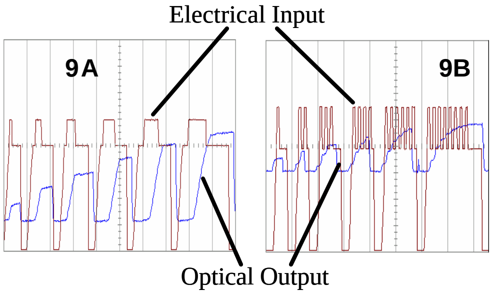

Figure 9 Grayscale rendition of a typical Microcup® EPD: (9A) by pulse width modulation at 15 V with a variable pulse width from 20~120 msec; and (9B) by pulse count modulation at 20V with a fixed pulse width of 15 msec.

6. Conclusions

High performance active and passive matrix Microcup® EPDs have been prepared by the SiPix roll-to-roll manufacturing process at very low cost and high throughput. The unique Microcup® structure and top-sealing processes results in super physicomechanical properties and format flexibility. They also allow the compositions of the electrophoretic fluid, the Microcups®, and the top-sealing and adhesive layers be optimized independently for optimum display performances. Plastic PMEPDs having threshold voltages ranging from 5 to 50V with a sharp gamma, fast response time, super image bistability, and wide temperature latitude have been demonstrated by using a simple row/column ITO electrode design. Satisfactory mid-tone image bistability and high gray levels have also been demonstrated without tradeoff in the pixel resolution. Microcup® AMEPDs based on a-Si TFT have also been demonstrated. The top-sealing layer has shown great barrier properties for a satisfactory green time and process window for the converting and lamination processes. The 1st generation prototype has shown a contrast ratio of $\geq$8 and a frame rate of $\leq$ 0.5 sec. at an operation voltage of $\leq \pm$10 volts.

7. References

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